STUDY ON APPLICATION

OF

NUCLEAR ELECTRICAL POWER

TO

MANNED ORBITING SPACE STATIONS

PHASE III
SNAP-8 EVALUATION AND DEVELOPMENT
PROGRAM RECOMMENDATIONS

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LEWIS RESEARCH CENTER

21000 BROOKPARK ROAD

CLEVELAND, OHIO

7 SEPTEMBER 1964

GENERAL ⊛ ELECTRIC

MISSILE AND SPACE DIVISION

GENERAL ⓖⓔ ELECTRIC
COMPANY

MISSILE AND

SPACE DIVISION

September 11, 1964

Subject: Contract NAS3-4160
          Topical Report No. 3

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The Missile and Space Division of the General Electric Company encloses herewith Topical Report No. 3 prepared under subject Contract. This Report is furnished to you in accordance with instructions from NASA, Lewis Research Center.
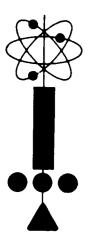
Very truly yours,

A. A. Gayuski
Contract Administrator

AAG:njs

Enclosures

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LIST OF NOMENCLATURE

A consistent set of nomenclature is used in this report as follows:

- Reference SNAP-8 --------------------the entire SNAP-8 system currently being developed for unmanned applications.

- Electrical Generating System (EGS) or --the entirety of a nuclear power system Nuclear Powerplant including reactor, power conversion loops and controls.

- Power Conversion System (PCS) or -----the power conversion equipment or Power Conversion Loops (PCL) loops exclusive of the reactor and the reactor loop components.

- Pump/Motor Assembly (PMA) ----------a pump and its motor.

1. INTRODUCTION

This report presents the results obtained during the Third and final phase of the study on application of nuclear-electric power to manned orbiting space stations. The program was conducted by the Advanced Nuclear Systems Engineering component of the General Electric Company under NASA contract NAS3-4160, and was directed by the Lewis Research Center.

The overall purposes of the study were:

    a.   Evaluation of nuclear systems as the prime source of electric power for manned space stations and examination of questions relating to the feasibility of this application.

    b.   Development of parametric data to aid the space station designer in the integration of the power supply with the station, and to aid the powerplant designer in adapting the plant to the space station application.

    c.   Preparation of a preliminary powerplant design based upon the SNAP-8 reactor applied to a specific station.

    d.   Provision of specifications to guide the development of SNAP nuclear power systems for maximum compatibility with the manned space station application.

The study was scheduled for, and completed, in twelve months. The first four months were devoted to Phase I which dealt largely with the first objective and portions of the second. Document 63SD865[1] describes the results of Phase I which considered powerplant cycle selection, interactions between the station and powerplant for various space station configurations and nuclear hazards.

The second six months were devoted to Phase II in which consideration was given to the application of SNAP-8 to a specific space station. Questions studied included methods of increasing power-system reliability, station/power-system interactions, shielding, modifications of the SNAP-8 Hg Rankine cycle and power system design. The results are described in documents 64SD647[2] and 64SD767[3].

(1)   "Study on Application of Nuclear Electric Power to Manned Orbiting Space Stations: Phase I, Feasibility Studies and Parametric Data", Document No. 63SD865, 20 Dec. 1963.

(2)   "Study on Application of Nuclear Electric Power to Manned Orbiting Space Stations: Phase II, Station/Powerplant Integration Studies", Document No. 64SD647, 5 June 1964.

(3)   "SNAP-8 Reactor Support Data", Appendix A to (2) above; classified Confidential-Restricted Data; Document No. 64SD767, 5 June 1964.

The present report describes the results obtained in the last two months of the twelve month study. Factors studied include the design considerations for replacement powerplants, methods of assuring system re-start capability, instrumentation and controls for man-rating and SNAP-8 growth potential. A comparison of solar photovoltaic and SNAP-8 power systems at a power level of 40 KW for a large 3-spoke station is presented. Recommendations for providing information essential to man-rating from the present SNAP-8 development program are included.

A final report [4] presents a summary of the results obtained in Phases I, II, and III of the study.

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(4) "Study on Application of Nuclear Electric Power to Manned Orbiting Space Stations: Final Summary Report", Document No. 64SD913, 7 September 1964.

2. SUMMARY OF RESULTS

2.1 REPLACEMENT POWERPLANT

The completely assembled replacement powerplant will be launched by the Saturn IB and will be stored by attachment to the central hub of the 3-spoke station. Approximately 21,000 pounds of station stores can be included with the powerplant.

It is concluded that minimum complexity results if the system is launched and stored with the heat rejection loops filled with fluid. Flow at a low rate and thermal insulation must be provided to prevent freeze-up of the radiators. Circulation can be provided by the loop pump at reduced speed or a small auxiliary pump. The NaK heat rejection loops may also use a small EM pump. A radiator thermal shroud consisting of a rigid glass laminate over several layers of aluminized mylar will reduce total heat loss to less than 2 Kwt which can be supplied from station waste heat. The thermal shroud is jettisoned at start up.

2.2 RE-START CAPABILITY

There are at least three design areas that will determine the feasibility of shutdown and re-start in the manned space station application of SNAP-8.

   a. Multiple Mercury Injections — The present mercury injection system operates only once and does not include any provision for re-start; however, it appears that by relatively simple modification, the injection system can be modified to provide unlimited re-start capability. The necessary demonstration of performance can be incorporated in the present SNAP-8 test program.

   b. System Freezing — The heat rejection radiators will freeze in a few minutes after shutdown and therefore, must be provided with heat or thermally blanketed. Alternates exist, but it appears that disposable mylar shrouds can be used to decrease the heat rejection capability of the radiators to about 7 kw which is within the waste heat capability of the station. Flow at a low rate must be continued in the loops.

   c. Positive Reactor Shutdown — The present reactor is shutdown by explosive rejection of the reflector. A control drum drive that provides for control, scram and restart is presently being used on the SNAP-8 ground prototype reactor. With some redesign for positive drum lockout at final shutdown, the drive can be adapted to allow shutdown and restart.

2.3 INSTRUMENTATION AND CONTROLS

A conceptual design for an instrumentation, control, and protective system for a modified SNAP-8 powerplant was prepared to indicate the type of subsystems that typically can be used to increase reliability and to allow an assessment of the availability of the instruments that may be required.

The results indicate that the necessary instrumentation can be provided with the proper logic to increase system reliability and flexibility without appreciably increasing the likelihood of accidental shutdown. Instrumentation of the proper type is generally available in stock, prototype or development stages; however, adaptation and qualification to SNAP-8 launch and operation conditions will be required.

2.4 POWERPLANT SPECIFICATIONS

General specifications for the integration of SNAP-8 nuclear power systems with manned space stations were prepared. These specifications indicate that:

- Auxiliary power sources that are highly reliable and independent of the nuclear system must be provided.
- The attachment of the nuclear system to a rotating station has a significant affect on station-balance and stability that must be considered.
- Provision must be made for the storage of powerplants in orbit for periods up to one year.
- Plant check-out and start-up time must be reduced to a few hours at maximum.
- All maintenance will have to be evaluated and proven and any maintenance requiring greater than a given time will have to be excluded from consideration.
- A method that provides for unitized replacement of assembled powerplants will be required to minimize the drain on the auxiliary power sources.

2.5 SNAP-8 SYSTEM GROWTH POTENTIAL

A SNAP-8 Reactor with either single or parallel power conversion systems (PCS) may be used to obtain greater than the design power of 35 KWe. The reference SNAP-8 system with one PCS can provide a maximum output of about 48 KWe net with the alternator as the limiting component. With parallel PCS's, the maximum output is also about 48 KWe with the reactor at 600 KWt as the limiting component. The potential up-rating capability of the reactor is discussed in the Classified Appendix to this report.

Utilizing only fixed radiators, a SNAP-8 system with parallel PCS's will be limited to about 60 KWe by the present payload envelope dimensions of the Saturn IB.

2.6 COMPARISON OF SOLAR PHOTO-VOLTAIC AND SNAP-8 ELECTRIC POWER SYSTEMS

Solar photo-voltaic and SNAP-8 electric power systems were compared for the 3-spoke space station at a power level of 40 KWe. The comparison shows that:

- When all weights attributable to a power system are included, initial launch weights for solar photo-voltaic and SNAP-8 power systems are approximately equal.
- The yearly station re-supply requirements for a SNAP-8 system can be about 7000 pounds lower than those of the solar photo-voltaic system, resulting in a saving of $32,000,000 over a station life of 5 years.
- The total cost required to provide the first flight qualified system of both types is about equal.

If, in fact, there is to be more than one station, then the nuclear system with its significantly lower cost per system will result in large program savings.

2.7 DEVELOPMENT PROGRAM RECOMMENDATION

The recommendations are divided into technical recommendations that principally affect the design of SNAP-8 as a man-rated system and recommendations on the direction of further development. The technical recommendations are included in the discussion of:

- Improvements in shield calculational techniques and consideration of alternate shield materials,
- Reductions in reactor envelope to reduce shield weight,
- Re-arrangement of the NaK heat rejection loop components to allow continued operation with a condenser tube leak,
- A test to determine the feasibility of using one heat rejection loop to "defrost" a parallel loop,
- The use of alternate fluids with lower pumping points in the heat rejection loops to alleviate the problem of radiator freezing during shutdown,
- A back-up mercury boiler design, and
- Steps required to prove maintenance and repair techniques.

The program recommendations are included in the discussion of:

- A development program for a man-rated SNAP-8 system,
- The requirement for ground test systems,
- A conceptual design for a flight test configuration of a test system,
- Powerplant designs that are applicable for more than one mission, and
- Investigations of stability limitations on rotating stations.

3. POWER SYSTEMS

This section describes the power system and particularly;

- The method for storing the replacement powerplant aboard the station,
- The limiting design factors in attaining multiple re-start capability,
- The special instrumentation and control necessary for man-rating, and
- The general specifications for the integration of a SNAP-8 power system with a manned space station.

3.1 REPLACEMENT POWERPLANT

3.1.1 CONFIGURATION DESCRIPTION

The replacement nuclear powerplant for the 3-spoke space station includes the reactor, primary loop components, power conversion equipment, primary radiator, and the replaceable portion of the shield as a completely assembled and checked unit. In the launch configuration shown in Figure 3.1-1, a disposal propulsion unit, secondary radiators, and approximately 21,000 pounds of station resupply stores are included. The complete replacement unit is 38.5-feet high and has a diameter of 21.7 feet to match the Saturn IB booster. The height is within the overall limitation of 42.25 feet, and the center of gravity of the payload does not exceed the limitation of 11.2 feet from the booster interface.

The propulsion unit, described in the Second Topical Report, is used for disposal of the old reactor during the replacement procedure. During launch it is mounted inside the primary radiator, suspended from the framework which supports the power conversion equipment. Axial loads are taken by the four struts attaching close to the center of gravity of the propulsion unit. Struts at the upper end provide redundant lateral support. The supporting struts are spring-loaded to retract when the attachments are explosively released and thus prevent interference when the propulsion unit is removed.

The station resupply stores may be such consumable items as food, pressurized gasses, or liquid fuels. The stores are contained in modular compartments, small enough to be handled by one man in a near zero gravity field. The stores are mounted inside the

secondary radiator with minimum overhang, and shear directly into the radiator shell. The heavier stores are mounted closer to the booster interface in order to minimize the bending moment.

Replacement of the permanent shield is not part of normal powerplant replacement. However, failure of the reactor to separate during the disposal procedure may result in an emergency condition where it is necessary to separate the boom structure from the space station spoke. Under these circumstances, a replacement powerplant unit will have to include the permanent shield and boom structure. This can be accomplished within the 37,000-pound payload capability of the Saturn IB booster. However, the 17,000-pound permanent shield will have to be mounted close to the booster interface in order not to exceed limitations on the height of the payload center of gravity above the booster interface. After being placed in orbit, it would then be necessary to place the permanent shield in its normal position before the replacement unit is mated to the space station.

3.1.2 PRIMARY RADIATOR

The primary radiator is a conical frustrum with an area of 950 square feet. There are two differences between this configuration and that shown for the initial powerplant (Phase II Report, Figure 5.3-1). The reactor support structure extends at a constant cone angle to the top of the primary radiator to give a favorable aerodynamic shape, and additional stiffening material is added to the radiator structure. Whereas the original primary radiator is suspended from the hub of the space station and subjected to tension loads during launch, the replacement unit is mounted directly on the booster and is subjected to compression loads during launch. Added fin thickness and stiffening rings are necessary in order that the primary radiator be capable of sustaining launch loads without buckling.

These two modifications would be incorporated into the first powerplant in order to provide a single design for both initial and replacement units.

3.1.3 SECONDARY RADIATOR

The original secondary radiator launched with the space station can have a design life of five years and need not be replaced with the remainder of the powerplant. However,

Figure 3.1-1. Replacement Powerplant
Launch Configuration

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a replacement can be provided in the configuration shown in Figure 3.1-1 with little weight penalty. The launch capability of the Saturn IB is in excess of the replacement powerplant weight, leaving a substantial margin for additional payload. Additional structure is required to accommodate these stores; therefore, it is possible to design this structure so that it can also be used as a secondary radiator.

As shown in Section C of Figure 3.1-1, the secondary radiator is designed as a sandwich shell structure, using the radiator fin as the outer skin. The secondary radiator operates at a low enough temperature that organic adhesives can be used for bonding. At the edges of each bay, the sandwich structure is bevelled to transfer all loads to the outer skin. The outer skin at the joints has a milled doubler at the joints where the loads are transferred through the structural rings by mechanical fasteners. The sandwich core is potted in the transition area to give additional reinforcement.

An alternate design approach is to increase the secondary radiator fin thickness from 0.040 to 0.15, so that the radiator is capable of sustaining launch loads as a monocoque shell. This results in a slight decrease in radiator area and an increase in tube spacing. However, the sandwich structure is approximately 200 pounds lighter.

The joint between the secondary and primary radiators shown in Section A of Figure 3.1-1 is clamped by a V-band during launch, permitting launch loads to be transmitted across the joint. Prior to reactor start up, the band is explosively released. The two radiator sections are then restrained only by bolted attachments with radially slotted holes. This permits the primary radiator, which has a higher operating temperature, to expand radially with respect to the secondary radiator. Heat transfer from the primary radiator to the secondary is reduced by an insulator between the faying surfaces and by the elimination of contact pressure between them.

3.1.4 STRUCTURAL DESIGN

A. Load Criteria

The radiator structure was analyzed for launch loads. An arbitrary load condition was assumed, varying linearly as shown in Figure 3.1-2 to an equivalent axial limit load of 360,000 pounds at the booster interface. This represents an aerodynamic
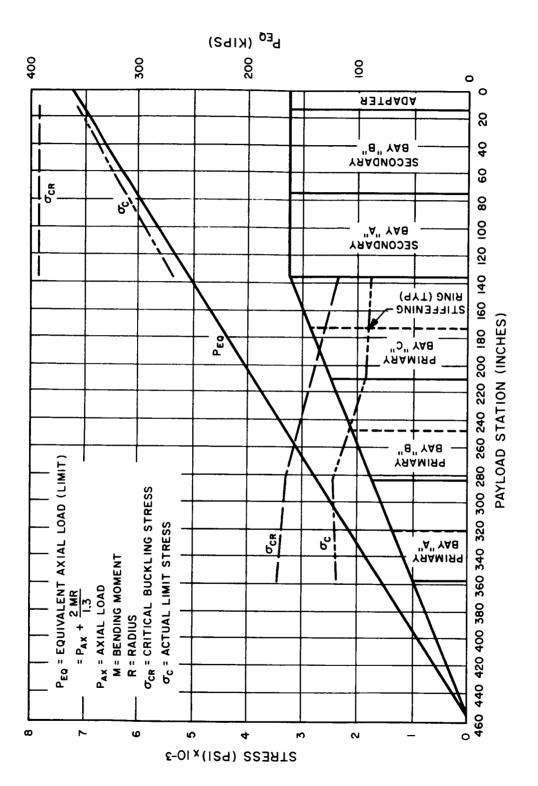
Figure 3.1-2. Replacement Powerplant Load and Stress Summary

loading due to wind shear. For comparison purposes, a steady state loading of 5g axial and 1.15g lateral results in the same load at the booster interface when combined as follows:

$$P_{EQ} = P_{AXIAL} + \frac{2MR}{1.3}$$

where

$$P_{EQ} = \text{Equivalent Axial Load}$$

$$P_{AXIAL} = \text{Axial Load}$$

$$P_{AXIAL} = W \cdot n_z$$

$$M = \text{Bending Moment}$$

$$M = W \cdot \ell \cdot n_y$$

$$R = \text{Radius}$$

$$W = \text{Payload Weight}$$

$$\ell = \text{Payload Distance above Booster Interface}$$

$$n_z = \text{Axial Load Factor}$$

$$n_y = \text{Lateral Load Factor}$$

B. Load Paths

The primary load paths during launch are through the radiator shell. The reactor and replacement shield are mounted on top of the primary radiator. The power conversion equipment and disposal propulsion unit are supported by a framework from the top of the primary radiator. The pressure bulkhead at the bottom of the primary radiator provides lateral support for the framework. The primary radiator is in turn supported by the secondary radiator. A short adapter section provides final load distribution to the booster interface. Separation takes place between the adapter and secondary radiator by explosive release of a V-band clamp.

Aerodynamic loads are taken by the reactor support structure shell and the radiator shell. The thermal shroud is segmented and considered non-structural.

C. Stress Analysis

The radiator shell structure was analyzed using the methods of Reference 1. Each bay was checked for general stability according to;

$$P_{CR} = 2\pi C E t^2 \cos^2 \alpha$$

where

P_{CR} = Critical Buckling Load

C = Buckling Correction Factor

E = Elastic Modulus

t = Thickness

α = Semi-Vertex Angle

Fin thickness in bay "C" of the primary radiator is increased from 0.07 in. to 0.09 in. and in bay "B" to 0.08 in. in order to prevent general instability buckling.

Fin-tube armor elements were checked for local instability (column buckling) between rings as follows:

$$\sigma_{CR} = \frac{C\pi^2 EI}{AL^2}$$

where

σ_{CR} = Critical Buckling Stress

C = Fixity Factor

E = Elastic Modulus

I = Moment of Inertia

A = Cross Section Area

L = Length

---

(1) "Handbook of Structural Stability"

NACA TN 3781   NACA TN 3783   NACA TN 3786

Stiffening rings are required in each of the three primary bays to prevent local instability buckling. The ring stiffness is determined by:

$$\bar{I}_f = \frac{C_F MD^2 d}{EL}$$

where:

C_F = Empirical Stiffness Parameter

$\quad\quad$ = 6.25×10^{-5}

M = Bending Moment

D = Diameter

d = Ring Spacing

E = Elastic Modulus

L = Column Length

A summary of actual and buckling stresses is plotted in Figure 3.1-2.

The secondary radiator was analyzed using an equivalent shell thickness for the sandwich structure,

$$t_{EQ} = \sqrt[3]{6\,th^2}$$

where:

t_{EQ} = Equivalent Thickness

t = Sandwich Skin Thickness

h = Sandwich Thickness

3.1.5 STORAGE IN SPACE

The replacement powerplant may be stored in orbit for a period up to one year. The problems encountered as a result of this storage period will differ, depending on whether the fluid systems are full or empty. The NaK in the primary loop provides support and damping for the reactor fuel elements during the dynamic environment of launch. Therefore, it is essential that the primary loop be filled prior to launch.

Mercury is injected into the secondary loop during powerplant start up. This leaves only the fluid in the heat rejection loops to be considered.

If the powerplant is stored with the heat rejection loops empty, a filling procedure must be performed prior to powerplant start up. This increases the time required to activate the powerplant, as well as increasing the system weight. The organic fluid used in the coolant-lubrication loop is not hazardous to handle and a simple filling procedure can be used. NaK for the primary heat rejection loop, however, must be stored in a reservoir that is pumped into the system and remotely controlled. Reservoirs, pumps, and valves for filling and venting must be provided in each of the redundant loops. Before being injected into the system, the NaK as well as all the components in the loop must be raised to a temperature above freezing. If the components and radiator are not heated, the NaK can refreeze in the cold passages, or cause structural damage due to thermal shock. The radiator can possibly be heated using solar energy by providing a covering with a high α/ϵ, however, this will require a selection of orbit and station attitude to avoid periods of eclipse.

A simpler and more reliable system results if the replacement powerplant is launched and stored with the fluid loops filled. The problem in this case is to maintain the powerplant at a temperature that prevents freezing. In the case of the coolant-lubrication loop, the temperature must be above the critical pumping temperature (about 125 to 150 °F). The approach shown in Figure 3.1-1 is to provide a thermal shroud to reduce heat loss from the radiators during launch and storage in space. Prior to launch, the powerplant can be heated from ground power. During storage, waste heat from the space station can be used to maintain temperature.

The thermal shroud, shown in Detail "B" of Figure 3.1-1 is a close fitting, rigid glass laminate over several layers of aluminized mylar. Direct contact with the radiator occurs only at the edges of the shroud segments, where the shroud is reinforced by edge members and restrained by circumferential straps. The flat shroud segments are deformed to the contour of the radiator so that explosive release of the restraining straps results in positive separation of the radiator.

The sequence for storage of the replacement powerplant is shown in Figure 3.1-3. After rendezvous with the space station and separating from the booster, the disposal propulsion unit is removed from inside the radiator using a logistics spacecraft. The

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SPACE STATION

REPLACEMENT UNIT

LOGISTICS SPACECRAFT

③ MATE WITH STATION HUB

DISPOSAL PROPULSION UNIT

LOGISTICS SPACECRAFT

② REMOVE DISPOSAL PROPULSION UNIT

⑤ CONNECT TO STATION POWER SOURCE FOR STORAGE

REPLACEMENT UNIT

BOOSTER

① SEPARATE FROM BOOSTER

④ PRESSURIZE & REMOVE STATION STORES
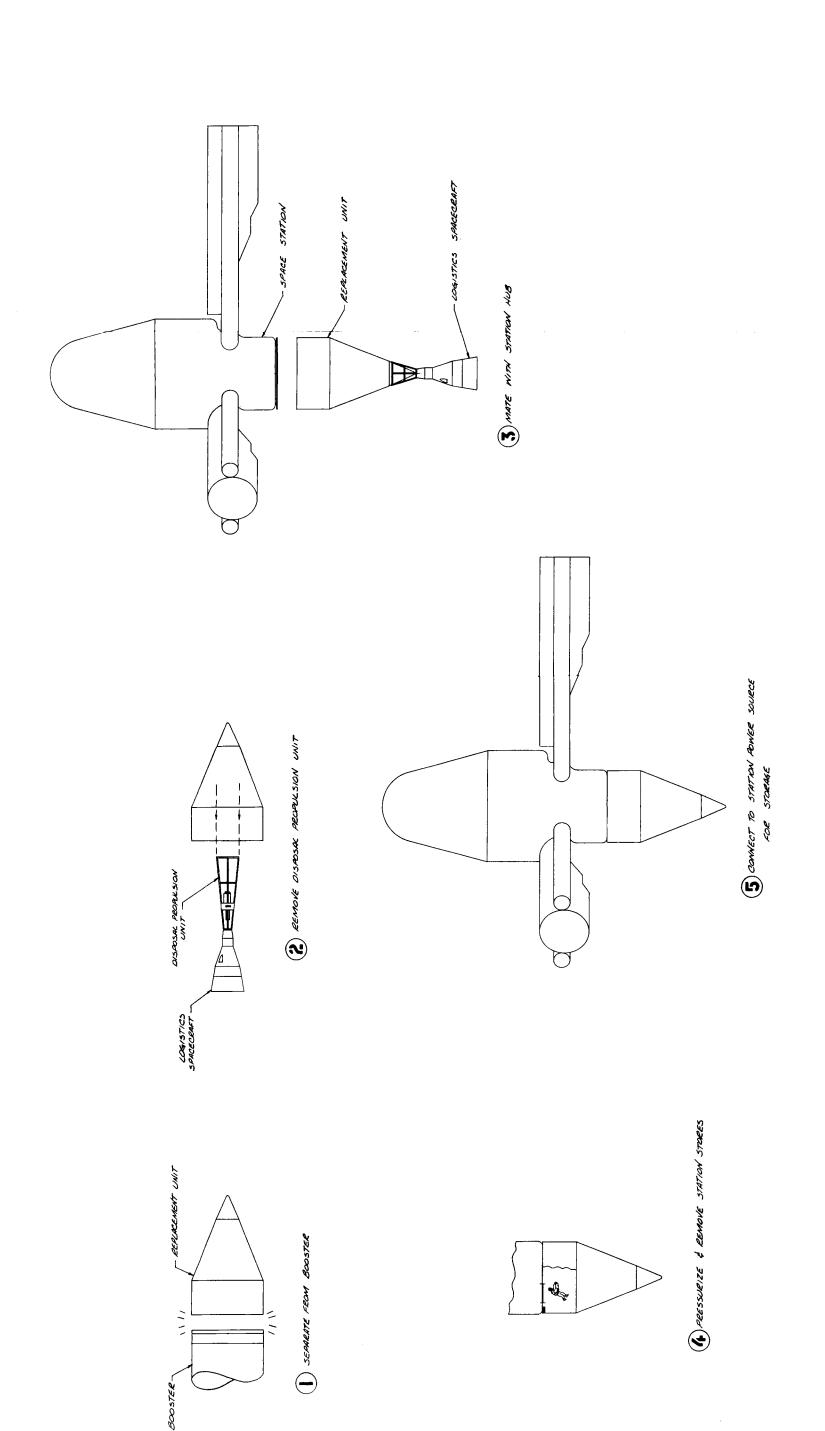
Figure 3.1-3. Powerplant Replacement
Unit Storage Sequence

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powerplant is then mated to the hub of the space station, using the same mating ring on the hub that is used to support the original powerplant during launch. The mating ring has an inflatable seal which allows the radiator shell to be pressurized to a partial atmosphere. The secondary radiator interior can then be entered by personnel from the space station to remove the resupply stores. Later, during storage, the interior of the primary radiator can be entered for periodic inspection and maintainance.

3.1.6 THERMAL REQUIREMENTS DURING STORAGE

The heat input required to maintain the replacement powerplant at an elavated temperature during storage is dependent upon the specified temperature and the effectiveness of the insulation. Assuming a multi-radiation barrier type of insulation, shown schematically in Figure 3.1-4, the steady state heat loss through the insulation is given by:

$$ q = \frac{\sigma(T_a^4 - T_b^4)}{\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} - 1} = \frac{\sigma(T_a^4 - T_b^4)}{R_{ab}} \tag{1} $$
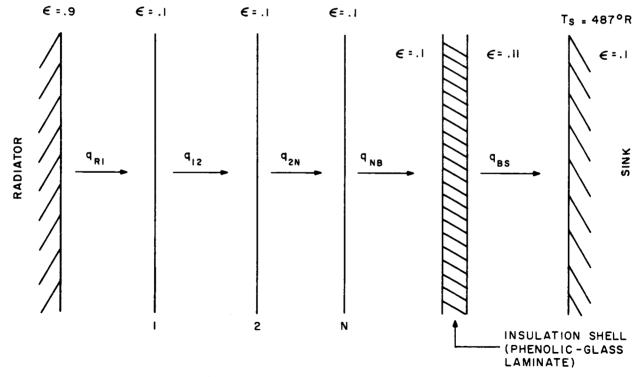
Figure 3.1-4. Schematic Diagram of Radiator Insulation

where

$$R_{ab} = \frac{1}{\epsilon_{ab}} = \frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} - 1$$

Assuming an emissivity $\epsilon = 0.1$ for aluminized mylar, and "N" layers between the radiators and support shell, the equivalent resistance of the insulation is

$$R_{EQ} = R_{R1} + R_{BS} + N \cdot R_{(N-1)N}$$

$$= \left(\frac{1}{.9} + \frac{1}{.1} - 1\right) + \left(\frac{1}{.1} + \frac{1}{1} - 1\right) + N\left(\frac{1}{.1} + \frac{1}{.1} - 1\right) \qquad (2)$$

$$= 10.11 + 10 + 19N$$

$$\approx 20 + 19N$$

A plot of Equation 1 is shown in Figure 3.1-5 for various values of R and for radiator effective temperatures in the 100°F to 400°F range. Sink temperature is taken as 27°F. The appropriate value of R can be determined from equation 2 by selecting the number of layers of aluminized mylar.

As an example, the replacement powerplant may be maintained at a temperature of 200°F, sufficiently above NaK and ET-278 freezing temperature to allow for transient conditions and thermal gradients throughout the system. Assuming four layers of aluminized mylar, R is 96 and the radiation heat loss, from Figure 3.1-5, is 0.7 watts/ft^2. The total heat loss from both primary and secondary radiators, with a total area of 1650 ft^2 is 1155 watts.

The above analysis considers heat transfer by radiation only and assumes that conduction between the layers may be considered negligible. Conduction losses will occur at the edges of the insulation segments where the panels are strapped down to the radiator.

Typically, the edge members will have a contact area equal to 1% of the total radiator area or 16.5 ft^2 and will result in an additional heat loss of about 700 watts.

When the powerplant is transferred to the operating position aboard the station boom, the insulation is jettisoned as shown in sequence 1, 2, and 3 of Figure 3.1-6 for start-up.
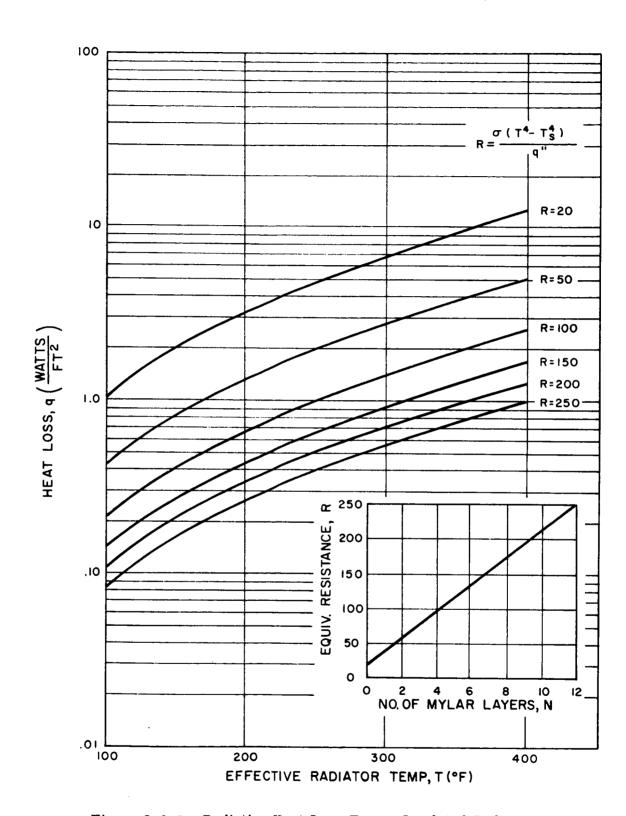
Figure 3.1-5.   Radiation Heat Loss For an Insulated Radiator

POWERPLANT

BOOM

SPACE STATION

THERMAL INSULATOR

①

- REPLACEMENT POWERPLANT DOCKED AND SECURED TO BOOM
- SPIN UP SPACE STATION
- BEGIN POWERPLANT START UP

REPLACEMENT POWERPLANT (STORED POSITION)

SECONDARY RADIATOR

THERMAL INSULATION

②

SPACE STATION

- JETTISON THERMAL INSULATION FROM SECONDARY RADIATOR

THERMAL INSULATION

POWERPLANT

SPACE STATION

③

- JETTISON THERMAL INSULATION FROM PRIMARY RADIATOR
- POWERPLANT IN FULL OPERATION

Figure 3.1-6. Powerplant Insulation Disposal Sequence

The heat required to balance the radiator loss during storage can be taken from waste heat sources on the space station. Waste heat from the station Life Support System could be used but likely it is at too low a temperature. The coolant-lubrication loop of the operating powerplant is only slightly higher in temperature than the temperature at which the replacement powerplant is to be maintained; therefore a high flow rate would be required and transmission losses would be critical. It has been proposed that waste heat from the primary heat rejection loop of the operating powerplant be utilized for some functions of the Life Support System. Unless another fluid is substituted for the NaK in the primary radiator, a heat exchanger to another fluid will be required to avoid the hazards of plumbing NaK through the space station. If such a system is used, it will be convenient to also provide heat for the replacement powerplant. During periods of powerplant shut-down, waste heat is available from the auxiliary power supply, typically fuel cells. Solar Energy is not available continuously unless restrictions are placed on the space station attitude and orbit. Electrical energy is continuously available and the most convenient to use, although it is the most expensive energy form.

Regardless of the form of the energy available, a problem exists in distributing heat to the large radiator area. If electrical power is used, heating elements can be built into the radiator structure; however, a more natural approach is to use the flow of the fluid through the radiator to distribute the heat. Circulation will be required in only one of the two redundant loops. The pumps can operate at a fraction of their normal operating flow rate and Aero-jet General indicates that no external lubrication or cooling is required up to 30% of design flow. If operation of the pumps during a one year storage period at a low flow rate results in an unacceptable degradation in pump performance or decrease in reliability, auxiliary pumps can be used. An auxiliary pump in parallel will require isolation with check valves. For the NaK loop, an E.M. pump in series can be used, if the constriction in the line when the pump is not operating is acceptable. Pump efficiency is not critical, since waste heat will raise the fluid temperature.

Heat can also be distributed to the radiators by radiation, from heaters located inside the radiator shell. However, the radiator is not designed for efficient heat transfer in this direction and it may be necessary to produce a high thermal gradient in order to maintain the radiator at the required temperature. Convective heat transfer can be utilized by pressurizing the interior of the radiator and using a circulating fan. The radiator is normally pressurized only during periods of powerplant maintenance.

3.2 RESTART CAPABILITY

There are many design considerations in providing shutdown and restart capability for the SNAP-8 system in space; however, there are at least three design areas of principal importance that will determine feasibility. These are:

- Providing for multiple mercury injections to the mercury loop,
- Preventing the freeze-up of the primary NaK and heat rejection loops, and
- Providing for reactor shutdown without rejection of the reflector.

3.2.1 MERCURY INJECTION SYSTEM

In the present SNAP-8 system, an injection system (Figure 3.2-1) is used to establish flow and a vapor-liquid interface in the condenser prior to the start of the mercury pump. This system operates only once and does not include any provision for restart; however, by relatively simple modification, the injection system can be modified to provide unlimited restart capability.

When used with a space station, artifical gravity will possibly be available due to station rotation and could be used to simplify plant start-up; however, it is considered undesirable to restrict the system to requiring gravity. Such a restriction is unnecessary and greater operational flexibility is included if a single start-up system, operable either with or without gravity is provided.

The present mercury injection system operates as follows:

- The mercury loop is evacuated and the reactor is operating at a modest power level with heat rejected via the auxiliary heat exchanger to the primary heat exchanger to the primary heat rejection loop.
- The positive displacement pump is started which pumps oil into the mercury tank. The oil and mercury are separated by a bladder and flow to the pump suction is provided by gas pressure in the oil tank.
- The metering valve opens and the initial mercury is injected into the system via the injection valve which blocks flow toward the pump.
- The injection rate is increased in a ramp by the contoured opening of the metering valve to about 40% of rated flow.
- The mercury passes through the boiler, is vaporized and passes through the turbine to the condenser.
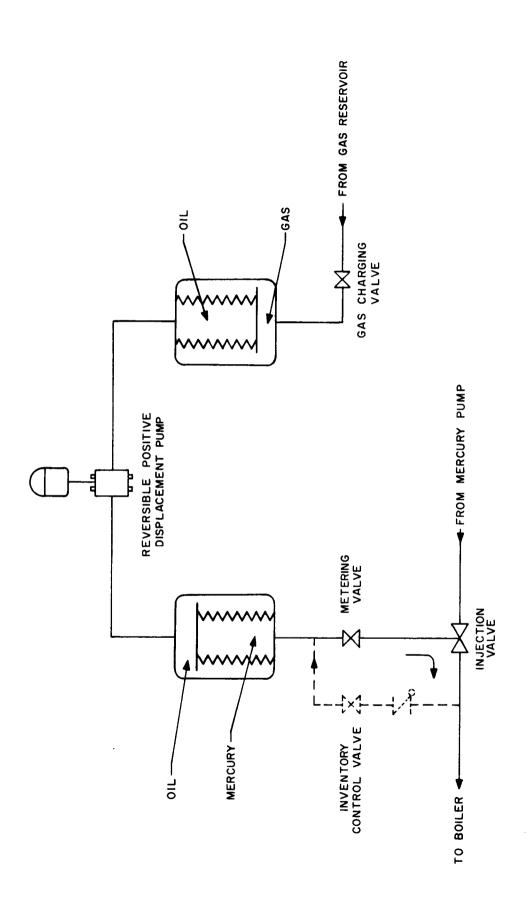
Figure 3.2-1. Mercury Injection System

- The turbine accelerates to speed, the mercury pump is started, and the injection of mercury is stopped.
- The system is operating at reduced flow rate and is brought to rated power by increasing mercury pump speed to rated.
- Normal design conditions are established.

Upon system shutdown in a zero-g environment, the mercury loop will be filled uniformly with a mixture of mercury liquid and vapor. The same start-up sequence could be repeated if the mercury could be removed by either vacuum pumping or by exhaust to space. However, vacuum pumping will require excessive power and will entail delays between shutdown and restart; whereas, exhaust to space will result in a loss of mercury. The effects of the mercury so released on the station would require examination. Therefore, it appears that the system must be restarted with the mercury liquid and vapor in the loop.

This can be accomplished if the mercury and oil tanks are oversized to allow the injection of two mercury charges, only one of which is injected for the initial start. The modified system will then operate as follows:

- With the mercury liquid and vapor in the loop piping, the re-start is initiated by the injection of the second charge of mercury in a programmed ramp input.
- The mercury liquid and vapor are pushed ahead of the newly injected mercury, the liquid is partially or completely vaporized in the boiler, and passes through the turbine to the condenser.
- The excess mercury in the loop collects in the condenser and the mercury pump is started at the proper time.
- The injection of the second charge of mercury is completed or stopped.

The system will then be operating at partial power and power can be increased by the normal automatic control system; however, full power may not be obtained because the condenser will be partially flooded due to the excess mercury in the loop. This will reduce the effective condensing area.

To remove the mercury, a bypass line can be included in the injection system as shown dotted in Figure 3.2-1. The outlet pressure of the mercury pump is about 350 psia and the inventory control valve can meter the excess mercury from the loop to the mercury tank. The positive displacement pump can operate in reverse to return oil to the oil

tank thus recompressing the gas for the next start-up. Thus, by the inclusion of a bypass line and an inventory control valve, the present injection system can be modified to provide restart capability.

The effect of this type of start up on the turbine was investigated. In a re-start, a mixture of mercury liquid and vapor will initially pass through the turbine and could possibly cause damage; however, Aero-jet General Corporation indicates that even during present start-ups, a large amount of moisture is expected as a result of the condensation that occurs during the heat-up transient, and that consequently, no deleterious affect would be expected. This conclusion is given support by the SNAP-2 turbine experience which has shown no turbine damage as a result of high moisture for short periods.

3.2.2 SYSTEM FREEZING

At system shutdown, the heat rejection loops will continue to reject heat to space and will rapidly cool to the freezing point if they are not protected. If both NaK heat rejection loops or both coolant-lube loops freeze, then plant re-start will be impossible without elaborate "de-frosting" measures. A radiator can be defrosted by tracing the structure with resistance heaters (this would require excessive power), orienting the radiator toward the sun (this would be a restriction on station operation), or by heating the radiator with chemical combustion energy (this involves problems in distributing the heat). None of the "de-frosting" techniques are attractive and, therefore, it appears that at least one each of the two sets of heat rejection loops must be kept fluid.

The emphasis here is placed on the heat rejection loops; however, the primary NaK loop must also be kept fluid. This is a less severe problem because flow must be maintained in any case to remove reactor decay heat and because the heat rejection area is minute compared to that of the radiators.

A. Radiator Cooling Rate

Eutectic NaK and ET-378 both have pour points of about 10°F. Pure eutectic NaK can be pumped at temperatures approaching the pour point; however, ET-378 cannot be pumped at temperatures below about 125°F. Therefore, for an adequate margin, the coolant-lube loop should be maintained at a temperature above 175°F. The NaK should

not be allowed to closely approach 10 °F because of the unknown effect of impurities on the eutectic and a possible shift in concentration away from the eutectic. For this study, it is assumed that a minimum NaK temperature of about 150 °F will be maintained.

The average NaK radiator temperature as a function of time after shutdown is shown in Figure 3.2-2. The analysis considers the heat capacity of the radiator matrix and uses the decay power of the reactor as a heat source. The additional energy stored in the reactor and shield is not included and, therefore, the true cooling rate will be less than that shown. The Δ T from radiator inlet to outlet is about 75 °F at time zero and will decrease with time. After several minutes, the entire radiator will be very close to the average temperature. As shown, the radiator will not reach 150 °F until after 30 minutes giving ample time for actions to prevent radiator freezing.

A similar analysis was performed for the secondary coolant-lube radiators except that the heat source was assumed to be zero. The results are shown in Figure 3.2-3. Radiator Δ T is only 26 °F at time zero and, therefore, the average temperature closely represents the true radiator temperature. The radiators operate much closer to the limiting pumping temperature than do the NaK radiators and the time available before a temperature of 175 °F is reaches is only 6 minutes.

Figures 3.2-2 and 3.2-3 assume a sink temperature of 26° F. Lower temperatures would result in slightly faster cooling rates.

B. Radiator Thermal Shrouds

The total heat rejected from the secondary coolant-lube radiators at 175° F and the NaK radiators at 150° F will be about 43 KW. This is significantly more than will be available from waste heat sources aboard the station and chemical combustion using H_2 and O_2 (100% efficient) will require 1000 pounds of fuel for 2 days. As alternates, the radiators can be oriented toward the sun to increase the sink temperature, the lithium-hydride of the shield can be used for thermal storage, or the radiator can be provided with a thermal shroud. Only the latter alternate is attractive because the first restricts station orientation and the second will involve technical problems in providing for phase changes in the lithium-hydride.
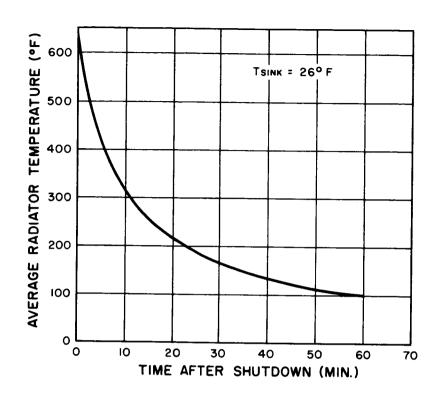
Figure 3.2-2. Temperature Response of Primary NaK Radiator
After Reactor Shut Down
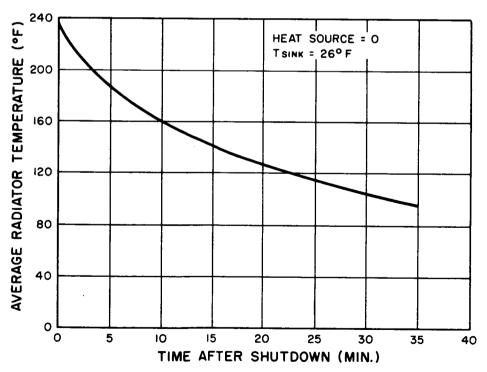
Figure 3.2-3. Temperature Response of Secondary Coolant-Lube Radiators
After Reactor Shut Down

Three types of thermal shrouds were investigated:

- "Venetian-blind" shutters along the radiator length,
- "Flower-petal" shutters, and
- Disposable thermal shrouds.

The "venetian-blind" shutters decrease radiator heat rejection capacity by 10 to 40% depending upon the particular design and both the "venetian-blind" and "flower-petal" shutters are mechanically complex. Therefore, a disposable thermal shroud is used to reduce radiator heat rejection.

The thermal shrouds are stored in a housing located between the secondary radiator and the adapter section, as shown in View "C" of Figure 3.1-1. The shrouds are aluminized-mylar, accordian folded into channel shaped ring segments, with secondary folds at six places around the circumference where the ring segments overlap. The ring segments are spring loaded into the housing and held by explosively released pins.

After the powerplant is removed from the station hub and before it is mounted on the spoke, the V-band clamp retaining the housing cover is explosively released and the cover is jettisoned by springs. This cover serves as a structural member during launch and attachment to the station hub. When powerplant shut down occurs, the release pins are explosively actuated, allowing the first shroud to deploy. Rotation of the space station and the inertia of the ring segments causes the shroud to extend and maintain tension. When the powerplant is restarted, the shroud is released by burning through with an imbedded heater wire. The second and subsequent shrouds are then available for use. This sequence of operations is illustrated in Figure 3.2-4.

A similar sequence can also be developed for a hub-mounted powerplant. However, since centripetal force will not be available, the De Havilland Rods (Phase II, Section 5.5-3), or some variant thereof, will have to be used to extend and hold the mylar shroud.

The mylar shrouds; including release mechanisms are quite light and add only 120 pounds to powerplant weight.

3-24

POWERPLANT

SHROUD

SPACE
STATION

- SHUT DOWN REACTOR FOR POWERPLANT
  MAINTENANCE
- EXTEND THERMAL INSULATING SHROUD

①

POWERPLANT

SPACE STATION

SHROUD

- SHROUD FULLY EXTENDED
- PERFORM POWERPLANT
  MAINTENANCE
- BEGIN POWERPLANT RESTART

②

POWERPLANT

SPACE
STATION

SHROUD

- RELEASE SHROUD
- POWERPLANT IN FULL OPERATION

③
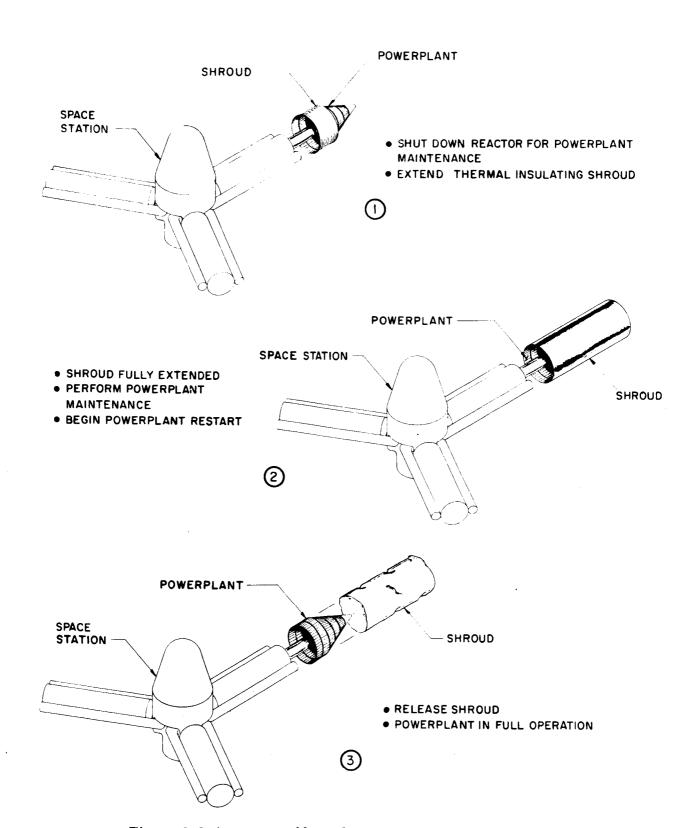
Figure 3.2-4. Disposable Mylar Thermal Shroud for Radiator

The effectiveness of the shroud in reducing the heat rejction capability of the radiators is shown in Figures 3.2-5 and 3.2-6. Shroud length is used as a parameter on the NaK radiator and fraction of radiator area covered is used as a parameter on the secondary coolant-lube radiator. Typical parameters are an "L/D" of 1.5 and an "F" of 1.0. At 150 and 175 °F respectively, the total heat loss is 23,500 Btu/hr (20,000 + 3500).

This energy can be provided as waste heat from the fuel cells which will be delivering 14 KWe during powerplant outages and from the reactor decay heat. Fuel cell waste heat will be 35,300 Btu/hr and a cell with a heat rejection temperature of 250 °F or above will be required. The Bacon cell provides heat rejection as high as 500 °F. Reactor decay heat will be 9000 Btu/hr even at two days. Thus, total power to the radiators can be as high as 44,300 Btu/hr. This is significantly greater than required and can be used to maintain the radiators at a higher temperature and, thereby, provide an additional safety margin.

The effect of the shroud on NaK radiator heat rejection at higher temperatures is shown in Figure 3.2-7. During start-up, reactor power is increased to about 50 KWt prior to the mercury injection into the system. This heat is rejected via the auxiliary heat exchanger from the primary NaK loop to the NaK heat rejection loop and thence to space. It is desireable that this heat be rejected with the shroud in place as otherwise, there may be difficulty in maintaining the proper temperature during the earlier start-up when reactor power is low. Figure 3.2-7 shows that up to 350,000 Btu/hr (102 KW) may be rejected with an L/D of 1.5 without exceeding the nominal radiator operating temperature of 650 °F.

Flow at a low rate must be maintained in one of each of the two sets of heat rejection loops in order to distribute the heat to the system and to prevent the formation of frozen lines. Flow can be provided by the loop pump at reduced speed, a small pump in parallel with the loop pump, or by a small EM pump (NaK Loops only). The power requirements are not an important factor as flow will be only 1/20 to 1/5 of rated. With pumping power proportional to the square to cube of flow, only a small fraction of a kilowatt will be required for the pumps.
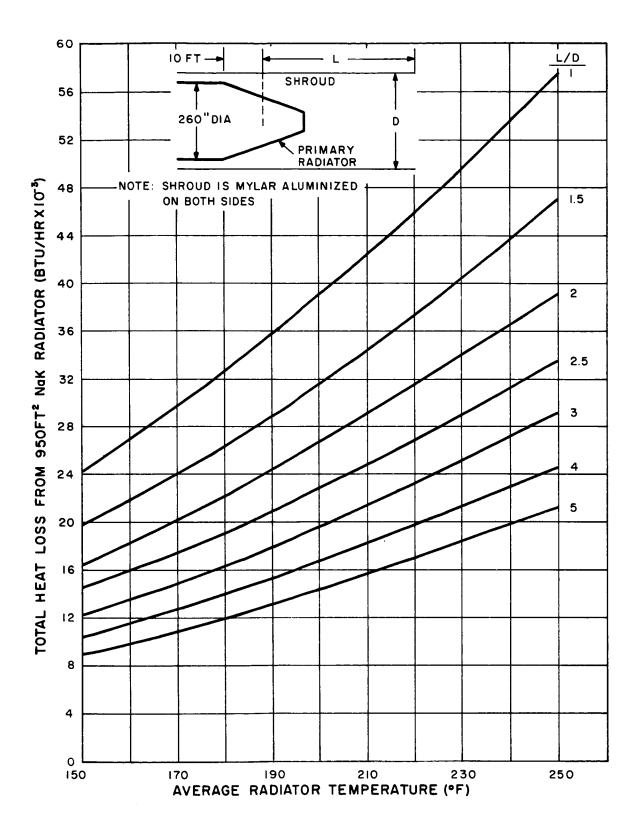
Figure 3.2-5. Heat Losses For Shrouded NaK Radiator
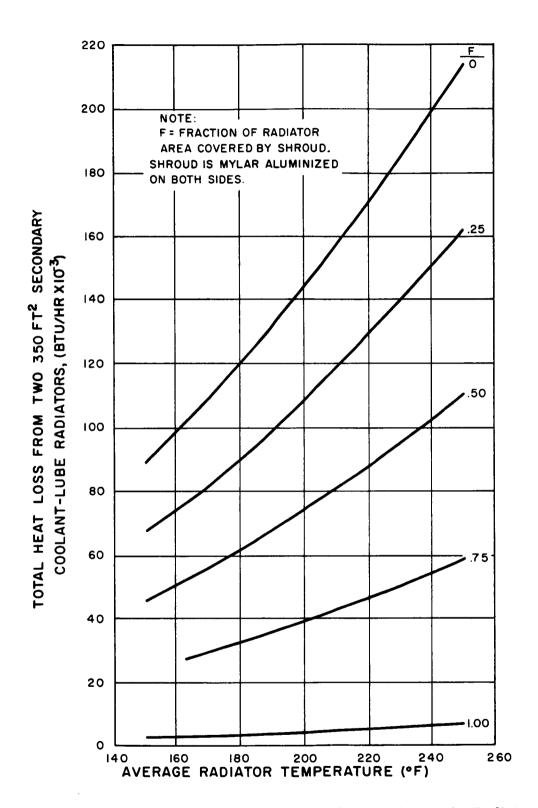
Figure 3.2-6. Heat Losses For Shrouded Secondary Coolant–Lube Radiator
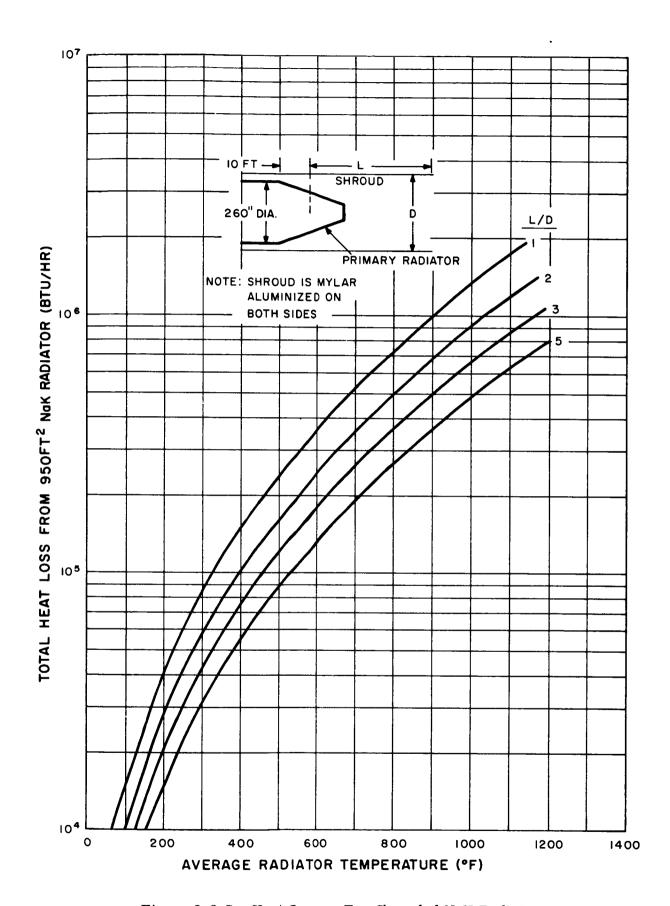
Figure 3.2-7. Heat Losses For Shrouded NaK Radiator

3.2.3 REACTOR SHUTDOWN MECHANISM

The present reactor is shutdown by an explosive release of the reflector and reflector control elements. Modification will obviously be required in order to attain restart capability. The experience obtained in designing and operating the ground prototype reactor is available and the control and scram mechanism developed for the ground prototype reactor can be adapted to allow control, scram and restart.

The SNAP 8 ground prototype control system employs a scram mechanism for each of the six control drums, and the drive motor (actuator) and scram mechanisms will be identical except that four units are right-hand and two are left-hand. A schematic of the drum drive-scram mechanism is shown in Figure 3.2-8 and a prototype mechanism is pictured in Figure 3.2-9.

Each drive unit is a complete package which mounts on top of the reflector and engages the drum drive shaft; the unit simulates flight-type control drive and also permits fail safe spring-powered scram of each control drum. The drive motor, bearings, gear end bell, and gear arrangement are the same as the flight model. This scram mechanism introduces no additional loads into the drum drive system and should give almost exact simulation of the flight system control performance.

Each unit is composed of a clock motor type of torsion spring for scam power, an electromagnetic clutch for disengaging the normal drive, and a compression spring stop for the drums at the end of the scram travel. The control drum drive motor is used to "cock" or preload the scram spring prior to reactor start-up to store the required scram energy.

The scram spring can be prewound and will remain loaded as long as the electric tooth clutch is energized; i.e., engaged. During normal control operation, the scram clutch is energized (closed) storing the scram spring energy, and the drive path is from the actuator through the pinion gear to the drive gear through the spring drive bellows, through the scram clutch teeth, and from the clutch body to the control drum drive shaft through a flexible coupling.

When scramming is required, the current to the actuator and scram clutch is interrupted simultaneously. The drive motor brake locks upon loss of motor power, and

CLUTCH COIL

SPRING DRIVE BELLOWS

SCRAM SPRING HOUSING

SCRAM SPRING

ACTUATOR BRAKE

ACTUATOR

ACTUATOR SUPPORT

VIEW C-C

STOP ARM

SNUBBER STRIKER

LIMIT SWITCHES

SNUBBER ASSEMBLY

LIMIT SWITCH

CLUTCH TEETH

DRUM DRIVE GEAR

SECTION A

SECTION B-B

SNUBBER COMPRESSION SPRING
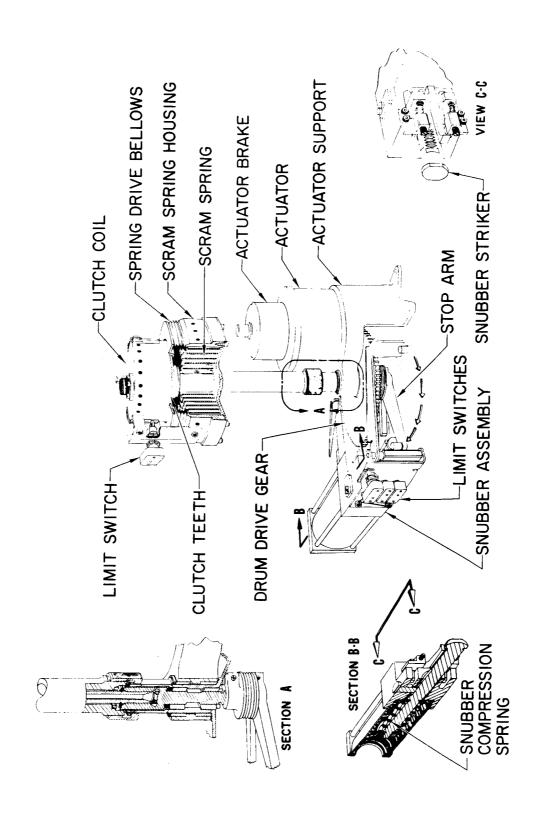
Figure 3.2-8. SNAP-8 DS Scram Mechanism Reflector Control System
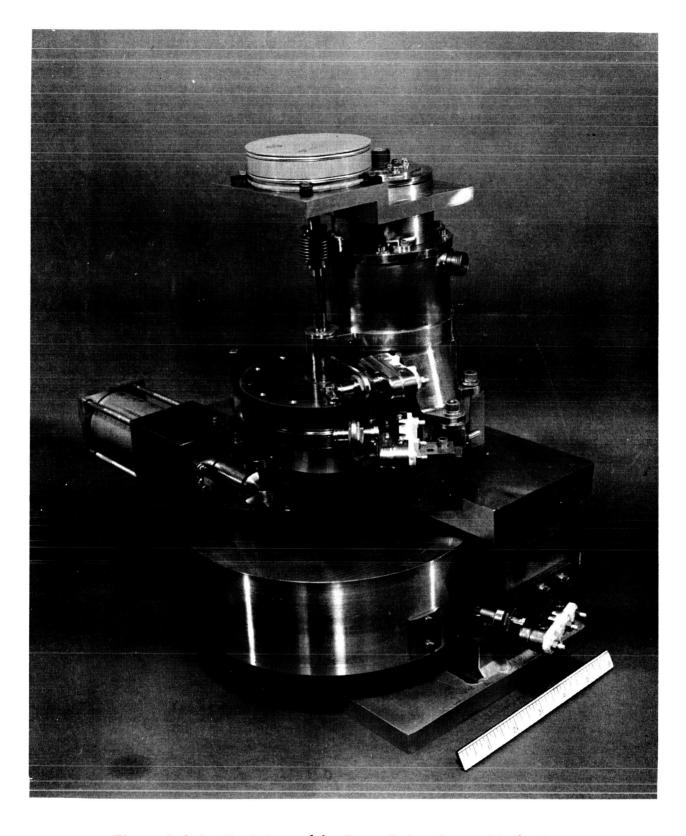
Figure 3.2-9. Prototype of the Drum Drive-Scram Mechanism

the scram clutch releases. The outside end of the scram spring is locked by the drive gear and pinion which are directly coupled to the motor and the brake shaft; the scram spring drives the torsion spring arbor, the coil section of the scram clutch, and consequently the control drum out of the control cavity, away from the core vessel, shutting down the reactor.

The energy of the scrammed control drum is absorbed by the stop arm of the drive shaft assembly striking the snubber striker and compressing the snubber compression spring. After completing the snubber stroke, the spring is prevented from returning by the action of a spring loaded ratchet. The ratchet engages the one-way teeth of the integral ratchet rack of the snubber shaft. A position indicating cam depresses a microswitch to indicate full scrammed drum position.

After scram and before restarting the reactor, the scram spring is rewound by de-energizing the clutch, and rotating the drive motor in the rewind direction. Because the control drum and spring arbor cannot rotate out further because the stop arm on the scram clutch is resting against the snubber striker, the rotation of the drive gear and spring housing rewinds the scram spring. A micro-switch mounted on the spring housing is depressed by the cam lobe on the coil section of the clutch to indicate that the scram spring is fully rewound. The scram clutch is then electrically closed, again locking the torsion spring energy. The drive motor can then rotate the control drum out of the snubber stroke sector. After the control drum is out of the snubber stroke, a ratchet dog trips the snubber ratchet which releases the compressed snubber spring. This spring is damped by a snubber release damping spring. The striker does not touch the drum arm upon release. Once out of the snubber region, the driving of the control drum through the motor pinion and gear is the same as before.

There are three switches mounted on the drum switch bracket; there is a full-in switch which indicates when the drum is $6 \pm 5°$ from the full-in position, a full-out switch which indicates that the drum is $109 \pm 1°$ from the full-in position, and another full-out switch which indicates drum beyond the $110°$ position from full-in. This last switch indicates that the drum is in the snubber range.

Some redesign is desirable for simplification, lightening, and for positive drum lock-out at final shutdown; however, the redesign would be simplified by the experience obtained in designing, manufacturing, and operating this drive.

3.3 INSTRUMENTATION AND CONTROLS

The Second Topical Report, Section 4.2, indicates that reliability can be increased by the incorporation of additional instrumentation, control, and protective systems in the reference SNAP-8 power system. This is conditional upon the inclusion of these sub-systems in such a manner as to not result in extreme system complexity or an appreciably increased likelihood of accidental shutdown.

A conceptual design for an instrumentation, control, and protective system for a modified SNAP-8 power system was prepared to indicate the type of sub-systems that typically can be used to increase reliability and to allow an assessment of the availability of the instruments that may be required.

The conceptual design includes:

- Instrumentation of the primary loop; each power conversion loop; each heat rejection loop; each secondary cooling loop, and the shield cooling loop.
- Automatic control of power plant:
  a) To follow the load under normal operating conditions.
  b) To effect the necessary change-over in case of failure of any portion of the powerplant to assure the continued operation of the powerplant.
- A protective system for the entire power plant to prevent hazardous situations from endangering either personnel or the space craft.

The modified SNAP-8 system and the additional instrumentation is shown in Figure 3.3-1.

3.3.1 INSTRUMENTATION

A variety of measurements are required throughout the SNAP-8 powerplant loops in order to satisfy the monitoring and control functions. The following tabulation illustrates the types of measurements to be performed:

- Temperature
- Pressure
- Differential Pressure
- Flow
- Rotational Displacement
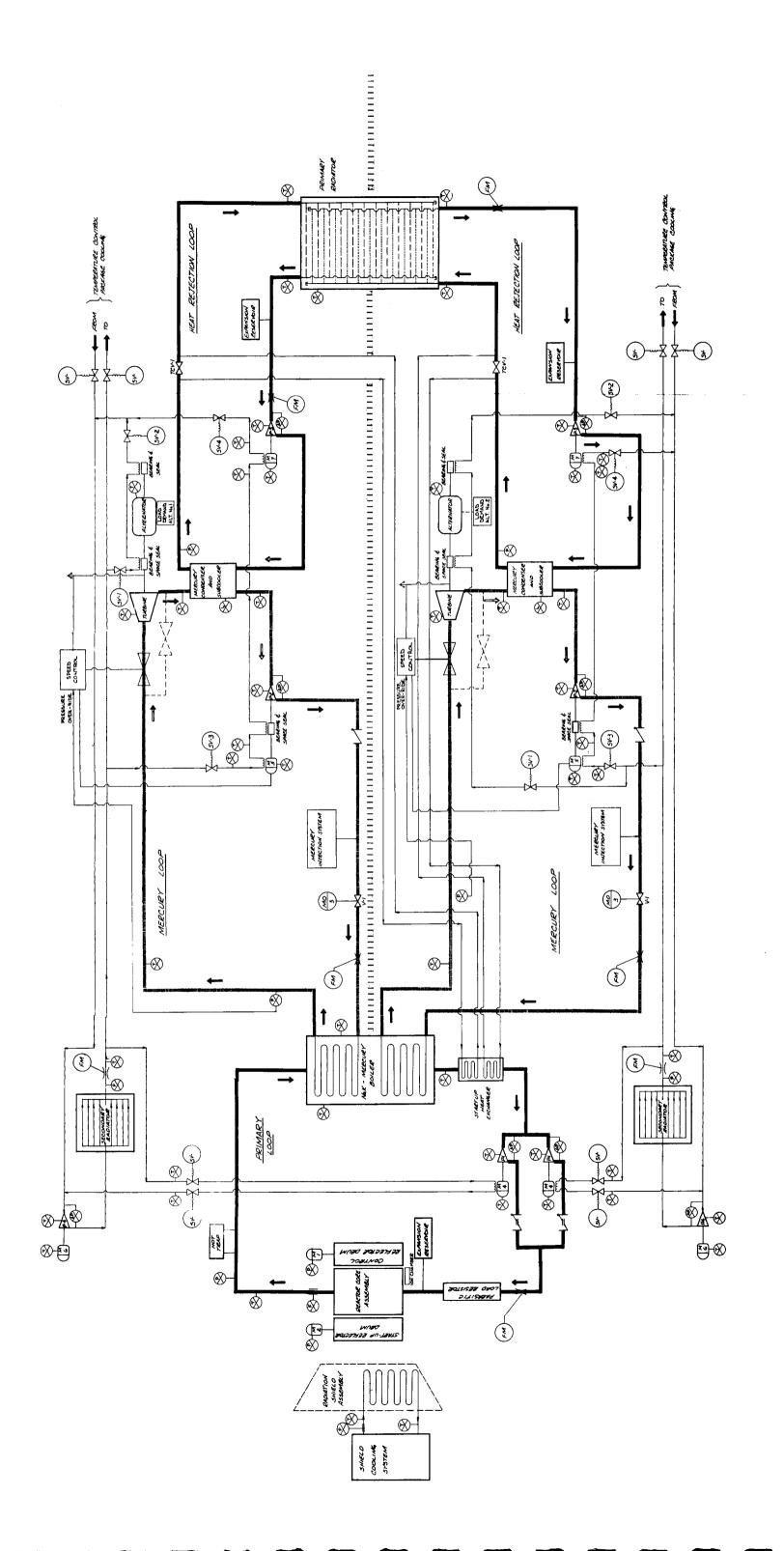
Figure 3.3-1. SNAP-8 Cycle With
Redundant Components in Parallel Loops

- Reactor Flux
- Liquid Level
- Electrical Line Frequency
- Voltage
- KVA

The quantity of identical sensors at each measurement point within the system is established in accordance with the protective system criteria derived for this program. These criteria are as follows:

- The protective system must sense and prevent all potentially hazardous situations; therefore, those parameters which reflect higher order hazard conditions must be instrumented and controlled with higher order redundancy.

- The powerplant system must rarely, if ever, shut down due to nonhazardous anomalies, such as a single channel instrumentation failure. This condition implies that multiple sensors be located at each measurement point with an appropriate weighting, or voting, factor assigned to each sensor.

- An alarm indication must be initiated for every out-of-tolerance condition in the system whether due to powerplant operating conditions or due to instrumentation drift. This alarm will permit on-board personnel to assess the malfunction and initiate corrective action.

- A majority of the sensors at each measurement point must indicate abnormal powerplant operation to cause either transfer of loop operations to a parallel loop or shutdown of the entire powerplant. In the latter case, transfer of loads to auxiliary power will be effected.

- A periodic, manual testing sequence must be rigorously followed to ensure proper instrumentation, control and protective system operation.

- Manual standardization of all equipment will be required to reduce the complexity of the instrumentation and eliminate the necessity of automatic self-checking hardware.

- For all critical parameters of the powerplant system, separate indicators for each sensor are provided to permit rapid diagnosis of any alarm condition and also provide greater operator confidence in each measurement.

A. Primary Loop Instrumentation

The primary loop instrumentation (Figure 3.3-1) consists of reactor start-up and control drum rotary position indicators; reactor inlet and outlet NaK flowmeters; reactor outlet NaK pressure gauges; pump differential pressure gauges; reactor and boiler outlet temperature thermocouples; reactor flux detectors, and numerous temperature monitors within the primary loop. Block diagrams of this instrumentation are shown on Figures 3.3-2a, 3.3-2b, 3.3-2c.
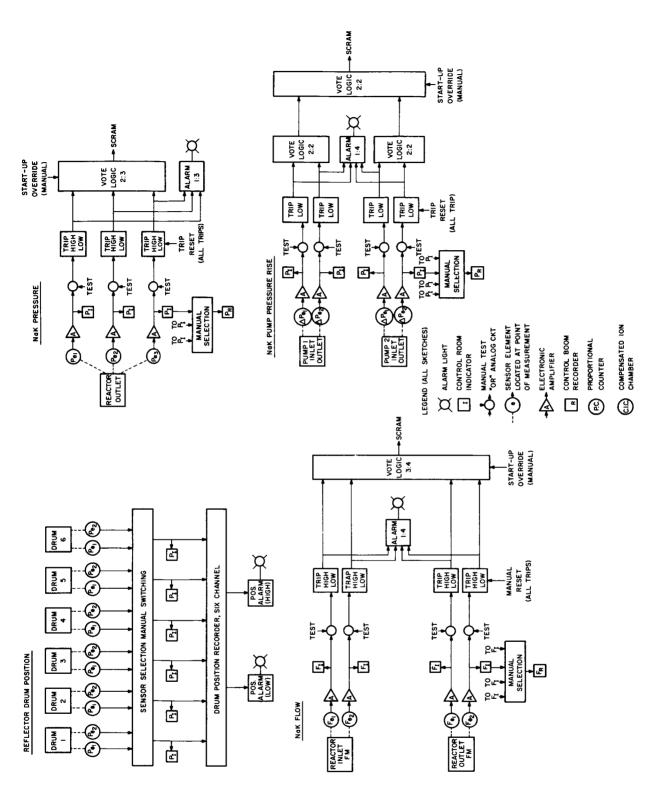
Figure 3.3-2(a). Primary NaK Loop Instrumentation
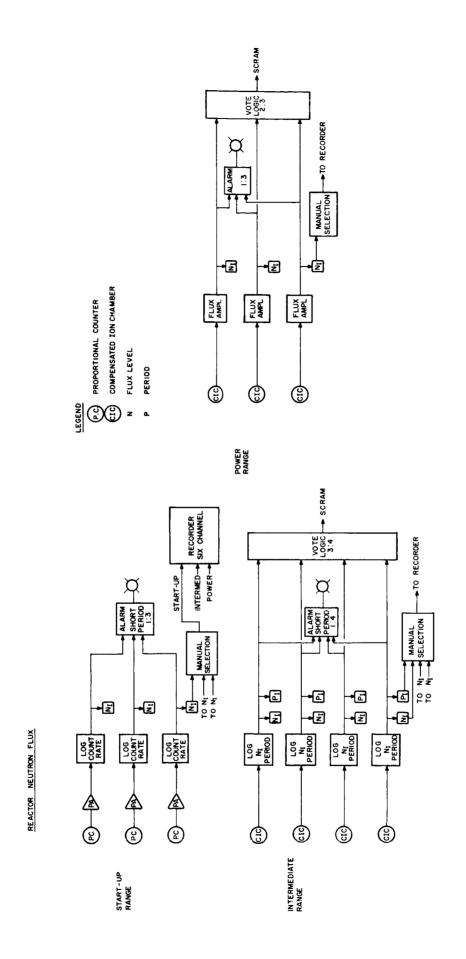
Figure 3.3-2(b). Primary NaK Loop Instrumentation
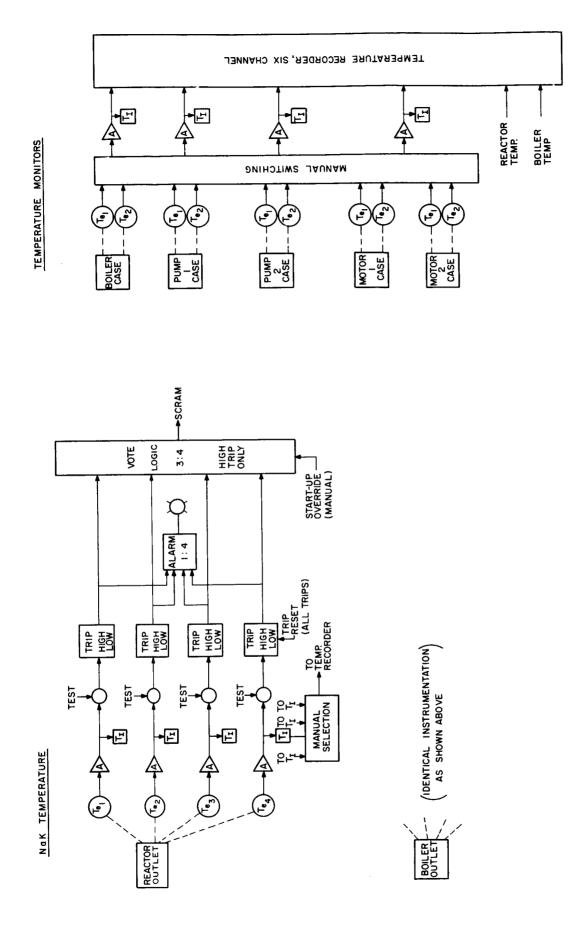
Figure 3.3-2(c). Primary NaK Loop Instrumentation

The control drum position indicators provide an alarm signal to the spacecraft personnel for either high or low limit conditions. No additional control is contemplated for these signals since other parameters may be used for detecting out of limit drum positions.

The choice of two flowmeters in the loop is dictated from considerations of operational readiness of the primary loop. This loop must be maintained "on-line" to the greatest practical extent and erroneous shutdowns due to faulty instrumentation must be reduced to a minimum level. On this basis, two flowmeters in different sections of the loop each having two sensing elements will provide the necessary redundancy and reliability. An alarm is initiated in the event that any one sensing element indicates high or low flow, and scram is initiated only when 3 of the 4 flow sensors indicate a malfunction.

The loop pressure is measured at the reactor outlet using 3 pressure sensors and is voted on a 2 out of 3 basis. The primary loop pumps are instrumented for pressure rise from inlet to outlet and each is voted on a 2 out of 2 basis with an additional 2 out of 2 majority vote for the two pumps in parallel. In this manner, powerplant scram is initiated only when all four sensors indicate low differential pressure.

Similarly, the primary loop temperature is measured at both reactor and boiler outlets and is majority voted on a 3 out of 4 basis at each location. Both high and low temperature conditions will cause an alarm; however, only high temperature initiates scram of the powerplant.

The reactor flux is measured over start-up, intermediate and power ranges using majority voting for alarm indication over the start-up range and for scram initiation over the two high flux ranges. Short period in either of the two upper ranges or high flux in the power region can be used to initiate scram if desired.

3.3.2 MERCURY LOOPS INSTRUMENTATION

The requirement for operational readiness of the mercury and NaK heat rejection loops is less stringent than that of the primary loop since parallel redundancy of loops is employed in the modified system. Therefore, an intermediate step between an alarm condition and powerplant scram is included; namely, the transfer of operation

from a disabled loop to the remaining loop. A block diagram for the mercury loops instrumentation is shown in Figures 3.3-3(a) and 3.3-3(b).

On this basis, a single flowmeter at the boiler inlet is included in each Hg loop with 3 flow sensors associated with each flowmeter. These sensors are voted on a 2 out of 3 basis for the initiation of transfer to the other loop, and will cause powerplant scram only is both loops become inoperative.

Pressure in each Hg loop is measured at the boiler outlet with 3 sensors at each location, and the majority voting is accomplished in the same manner as shown above for Hg flow.

The single Hg pump for each loop is instrumented for differential pressure rise in a similar manner as the primary loop pumps. Both sensors for a pump must indicate low pressure rise for a transfer command to be generated and both loops must be inoperative to initiate powerplant scram.

Since the power conversion loops are restricted in temperature by the primary loop temperature, monitoring of temperatures without voting is provided at the boiler, turbine and condenser outlets of each PC loop. Three thermocouples are provided at each location to ensure redundancy of measurement and indication for the operator.

Liquid Hg level measurement within the condenser is provided. A single level sensing element is included to provide an indication for the operator.

Instrumentation for the alternator encompasses output voltage and volt-amperes, KVA, for each phase and output frequency for each alternator. A high and low trip circuit is provided for each parameter and majority voting of each is accomplished in a similar manner to the aforementioned flow and pressure measurement of the Hg loops. However, manual switching of electrical loads among the three phases of a single alternator is provided to reduce the necessity for loop transfer under single phase fault conditions.

3.3.3 NaK HEAT REJECTION LOOPS INSTRUMENTATION

The instrumentation of the NaK Heat Rejection Loops (HRL), as shown in Figure 3.3-4 is very similar to that of the Hg loops. The sensors are similar or identical to those of the primary loop in that NaK is the fluid medium rather than Hg; however, the technique of instrumentation closely parallels the Hg loops in all other respects.
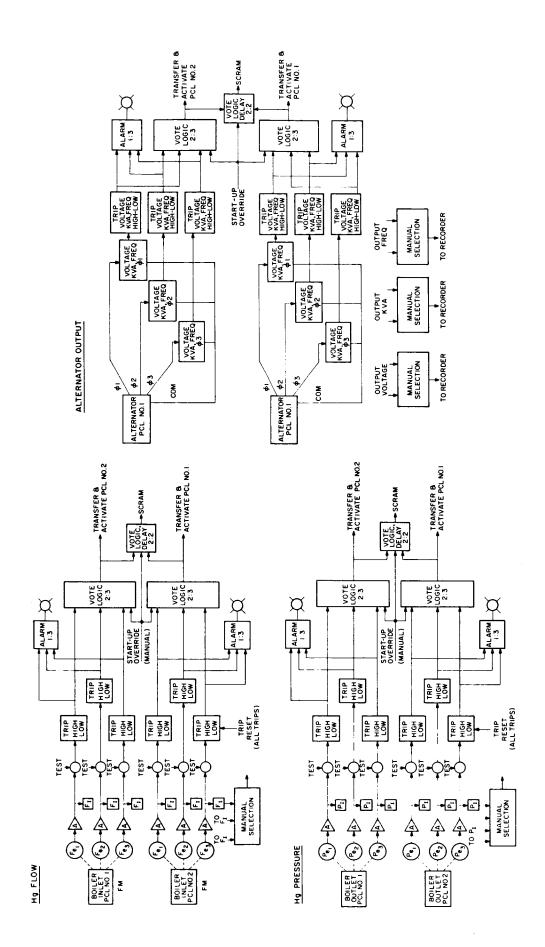
Figure 3.3-3(a). Mercury Loops Instrumentation

3-43
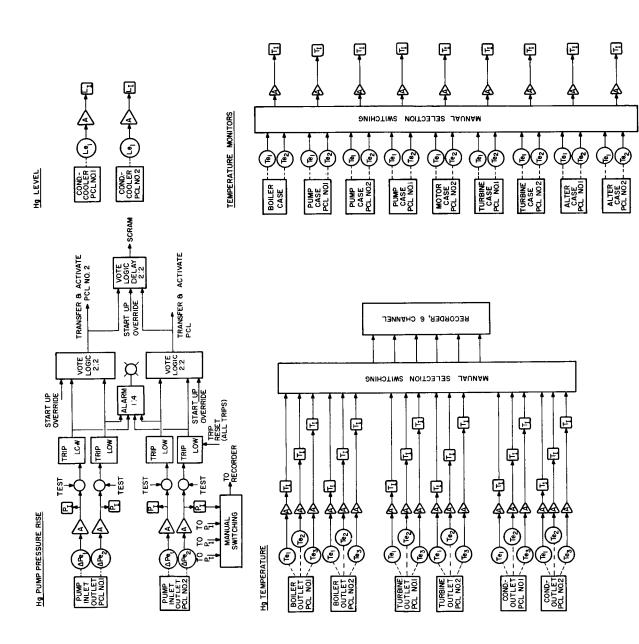
Figure 3.3-3(b). Mercury Loops Instrumentation

NaK TEMPERATURE

(IDENTICAL INSTRUMENTATION TO Hg TEMPERATURE IN Hg LOOPS)

RADIATOR INLET HRL NO. 1

RADIATOR INLET HRL NO. 2

RADIATOR OUTLET HRL NO. 1

RADIATOR OUTLET HRL NO. 2

TEMPERATURE MONITORS

(IDENTICAL INSTRUMENTATION TO TEMPERATURE MONITORS IN Hg LOOPS)

RADIATOR

PUMP CASE HRL NO. 1

PUMP CASE HRL NO. 2

MOTOR CASE HRL NO. 1

MOTOR CASE HRL NO. 2

NaK FLOW

(IDENTICAL INSTRUMENTATION TO Hg FLOW IN Hg LOOPS)

COND. INLET HRL NO. 1 FM

COND. INLET HRL NO. 2 FM

NaK PRESSURE

COND OUTLET HRL NO. 1

COND OUTLET HRL NO. 2

NaK PUMP PRESSURE RISE

(IDENTICAL INSTRUMENTATION TO Hg PUMP IN Hg LOOPS)

PUMP INLET OUTLET HRL NO. 1

PUMP INLET OUTLET HRL NO. 2

Figure 3.3-4. NaK Heat Rejection Loops Instrumentation

Flow is monitored with a single flowmeter and 3 sensor elements at the condenser inlet of each loop and is voted on a 2 out of 3 basis for transfer activation.

Pressure measurement consists of three sensors at the condenser outlet of each loop and is voted on a 2 out of 3 basis for transfer to the other HRL. The NaK pump of each loop is instrumented with two differential pressure sensors in a similar manner to the pump of the Hg loops.

Temperature in the HRL is used for indication purposes only and consists of redundant thermocouples located at the primary radiator inlet and outlet.

3.3.4 SHIELD AND COOLANT-LUBE LOOPS INSTRUMENTATION

The shield cooling loop, Figure 5.7-10, Second Topical Report, taps a portion of the primary loop NaK flow and transfers the shield cooling loop heat to the Hg loops in a heat exchanger. Since only a small portion of the primary loop NaK flow will be diverted to the shield cooling loop, the existing primary loop instrumentation need only be supplemented to properly monitor the shield cooling loop. Therefore, it is necessary that only flow and temperature be measured within the shield cooling loop. This is shown on Figure 3.3-5. However, since flow measurement of the shield cooling loop may be inferred from existing parameter measurements within the primary loop, the proposed flowmeter may be deleted by proper modification of the shield cooling loop instrumentation.

On the other hand, the secondary coolant-lube loops must be instrumented in a manner similar to the Hg and Heat Rejection Loops because of the motor and bearing coolant interfaces among these loops. Figure 3.3-5 shows the instrumentation for these loops.

3.3.5 DATA DISPLAY AND RECORDING

The data display for the control room operator can use individual indicators for each sensor in critical portions of the instrumentation system. This technique requires a greater quantity of amplifiers and indicators than other methods; however, certain advantages result from this choice:

- The operator may directly compare all sensors at each measurement point at any time.
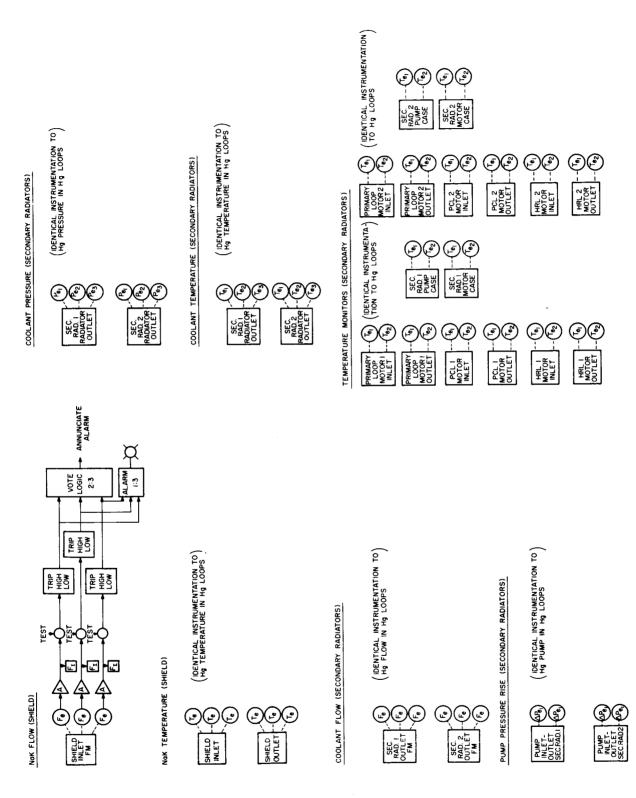
Figure 3.3-5. Shield and Coolant-Lube Loops Instrumentation

- Human assessment of each situation, including the empirical determination of a confidence factor for each measurement, is possible since two or more sensors at a given location must display identical data, within limit, to maintain normal operation of the system.

- Long term drift of a particular sensor channel may be determined from sequential data readings, thereby, permitting the operator to introduce compensation within the instrumentation system if desired.

- The recording of data may be reduced to a single sensor channel at each location unless additional recordings are desired by the operator.

- Periodic testing of the instrumentation system to fulfill the protective system requirements permits the operator to confirm the calibration of both indicators and recorders at each test interval.

Therefore, the data recording technique for the instrumentation system can utilize a minimum number of recorder channels with manual switching among the sensor channels to permit comprehensive data logging if desired by the operator.

3.3.6 CONTROL SYSTEM

To operate two turbine/alternators in parallel, a control system is required to allow each to follow load changes. A possible SNAP-8 powerplant control system is shown in block diagram on Figure 3.3-6. This system is of a general nature by necessity; however, it does present the necessary elements (1) for an automatic control system based on an appraisal of the degree of control required for the powerplant; the remaining controls of a less serious nature are to be performed manually. This approach is used to minimize the complexity, weight and cost relative to a more elaborate and complex control system.

This brief examination has not included consideration of the dynamics of the control system or the response to accident conditions and; consequently, no definitive conclusions can be drawn. This is particularly important because definitive recommendations could only be made after an exhaustive examination of the present control system and modifications thereof and of alternate control systems. The alternator electrical output controls the flow rate of its associated Hg loop by adjusting the motor speed of the Hg pump.

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(1) Reference 13, Chapters 7 and 8
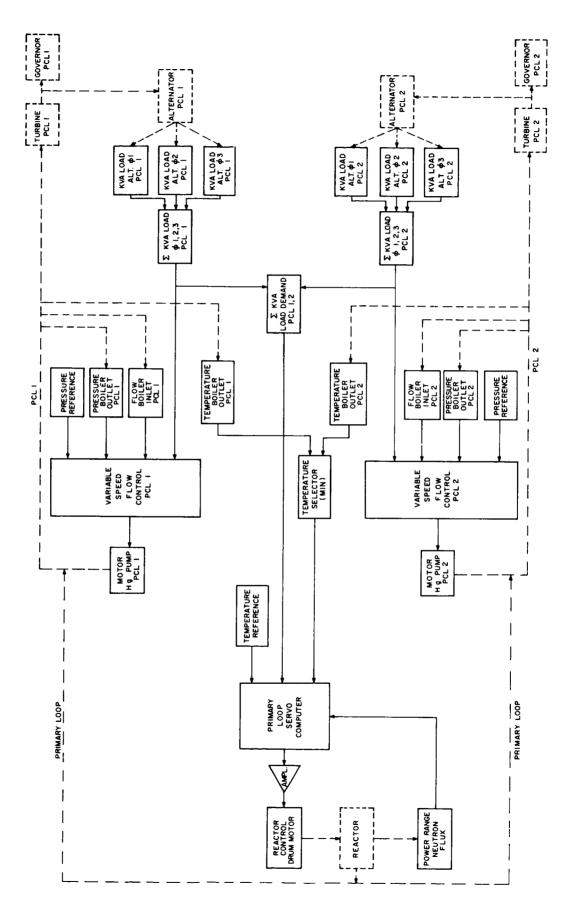
Figure 3.3-6. Control System Block Diagram

In addition, the summed electrical output of the two alternators is used to control the reactor power output by adjusting the position of the reactor control reflector drums. Thus, changes in the electrical KVA demanded by the load are reflected in both the primary and power conversion loop operating conditions.

As shown a load following signal is generated in proportion to the electrical demand on the alternator and is compared with a signal proportional to the Hg flow. In addition, a signal proportional to Hg loop pressure is compared with a predetermined reference pressure for that loop. In accordance with these four input signals, the flow controller develops a control signal for speed correction of the pump motor, and maintains proper operating conditions in the power conversion loop. An additional safety feature is provided for high pressure conditions in the loop in which the turbine inlet is throttled by a pressure override valve.

In the primary loop, the servo computer functions to establish and maintain proper operating conditions in accordance with the total spacecraft electrical load demand. A load following signal proportional to the total demand on both alternators is compared with a signal proportional to the reactor power range neutron flux level. In addition, a signal representing the minimum operating temperature at the boiler outlet is compared with a predetermined reference temperature. These input signals are applied to the servo computer to generate a control signal for positioning of the reactor control reflector drums. The control reflector drums serve to complete the control loop by adjusting the reactor operating power level in accordance with the servo computer output control signal.

This is only one of several possible control systems and it is described because it is relatively simple and it provides a rapid response of reactor power to load demand to enhance load following. It may be possible also to use the present reactor control system which adjusts drum position to maintain reactor outlet temperature. This system is simpler and, therefore, desirable; however, the thermal lag of the system may hinder load following. An evaluation of system dynamics is required for a comparison of alternate systems.

3.3.7 PROTECTIVE SYSTEM

The salient design criteria for the protective system are included with the Instrumentation portion of this report because of the strong influence of the former on the latter.

These criteria are incorporated into both the instrumentation and control phases of this study. Figure 3.3-7 is a sequence diagram for the protective system. It illustrates three major event states, as follows:

- Alarm, which alerts the operating personnel that one or more sensor channels have become tripped.

- Transfer, which signifies that one of two parallel redundant loops is disabled, and causes all operating conditions of the disabled loop to be transferred to the parallel operating loop.

- Scram, which indicates a system malfunction of the powerplant, and initiates shutdown of all loops simultaneously. At the same time loads are transferred to the auxiliary power sources.

The influence of the various parameter measurements upon the system alarm, transfer and scram states is shown for each loop on the sequence diagram.

The selection of a proper weighting, or voting, factor for the protective system is in accordance with standard practice (Ref. 2) in the nuclear power reactor industry. In the referenced article by I.M. Jacobs, an analysis of redundancy within a typical nuclear powerplant instrumentation system illustrates the trade-off between safety of operation and the rate of false scrams of the system:

let, R_s = the rate of false scrams due to spurious faults

$$FM = \frac{\text{total time between testing*}}{\text{time unprotected between testing}} \approx \text{safety of operation}$$

In the author's example, a typical situation is assumed as follows:

12 spurious faults per year
2 operational faults per year
10 minute reset time to place a faulty controller back in operation
8 hours between test intervals

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*Time between testing is defined as the interval between manual checks that assure proper operation of the particular system.
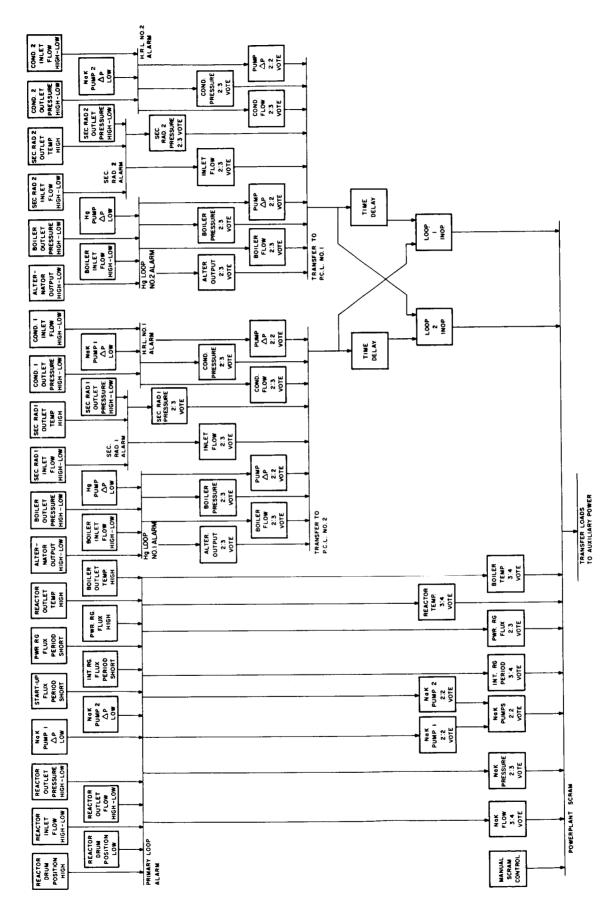
Figure 3.3-7. Protective System Sequence Diagram

Under these conditions, it is desired to minimize Rs and simultaneously maximize the figure of merit, FM. The following types of circuit redundancy yield solutions for these two variables as follows:

VOTING FACTOR	LOGIC EXPRESSION	Rs	FM
1:1	A	12.	1,096.
1:2	A + B	24.	901,500.
2:2	A • B	0.00548	548.
2:3	(A+B)•(B+C)•(C+A)	0.0164	300,500.
2:4 selected	(A+B)•(C+D)	0.0279	450,750.
2:4	A • (B+C) + B • (C+D) + D • (A+C)	0.0323	82,400,000.

From this example, it can be seen that as circuit redundancy is increased, the figure of merit term increases rapidly indicating that system safety is improved. However, for these same conditions, the rate of false scrams is also increased.

Therefore, for the SNAP-8 powerplant, the instrumentation redundancy utilizes 2 out of 3 coincidence for all critical measurements except for select primary loop measurements where 3 out of 4 is used to further reduce the incidence of false scrams with only a minor sacrifice in safety of the powerplant.

3.3.8 ADDITIONAL CONSIDERATIONS CONCERNING THE POWERPLANT CONTROLS

The evaluation of the instrumentation for the modified SNAP-8 system has indicated several design areas where additional consideration is required, these are:

- A system stability analysis will be required before detailed design of the control system can be initiated.

- Additional instrumentation to permit heat balance analyses may be incorporated into the system should this provision enhance an operator's assessment of system operation.

- A turbine by-pass valve, shown in the proposed system, appears to be a desirable addition to the powerplant. Of concern is the protection of the turbine from cooled Hg flow after reactor scram and subsequent cooling of the boiler.

3.3.9 INSTRUMENTATION AVAILABILITY

The variety of required measurements, as illustrated here, necessitates a large number of different components to perform the system instrumentation and control functions. Table 3.3-1 indicates the type of components that must be added to the basic SNAP-8 powerplant and provides a brief evaluation as to the development status of the components.

3.3.10 REFERENCES FOR SECTION 3.3

1. J. F. Cage, Jr. and G. D. Collins, "Pumps and Valves," The Reactor Handbook Engineering, Volume II, 1955, p. 342-359.

2. I. M. Jacobs, "Safety Systems for Nuclear Power Stations," AIEE Communications and Electronics, Nov., 1957, p. 670.

3. Julius Hyman, Jr., "Low Impedance Bridge for the Measurement of Level in Liquid Metals," The Review of Scientific Instruments, Volume 32, Number 7, July, 1961, p. 833-837.

4. S. Colussi, F. Fioroni and R. Marconero, "A DC Amplifier for Neutron Thermopiles or Thermocouples," UCRL Transactions 1021 (L), February, 1964.

5. J. P. Delisle, "Automatic Measurement of the Plugging Temperature of Sodium and of NaK," AEC-TR-6353, April, 1964.

6. K. A. Thomasson, "SNAP 2/10A Hydraulic Studies," NAA-SR-MEMO-9405, April, 1964.

7. F. O. Prescott, "Instrumentation," The Reactor Handbook, Engineering, Volume II, 1955, p. 359-366.

8. J. R. Burnett et al., Transducers for Nuclear Vehicles, Final Report, Volume II, ASD-TDR-62-551, January 24, 1962.

9. Nuclear Process Instrumentation and Controls Conference Record, ORNL 2695, May 20-22, 1958.

10. W. R. Miller, High Temperature Pressure Transmitter Evaluation, ORNL-2483, July, 1958.

TABLE 3.3-1. INSTRUMENTATION AVAILABILITY

FUNCTIONAL PART	POSSIBLE COMPONENT	KNOWN AVAILABILITY	CONSIDERATIONS
Temperature Sensor Medium Temp. Range	(1) Thermocouple	Stock item	(1) Low cost, rugged, approximate 1% accuracy
	(2) Resistance Thermometer	Stock item	(2) High cost, less rugged, approximate 0.3% accuracy
Temperature Sensor High Temp. Range	(1) Thermocouple	Some experience available	(1)
	(2) Resistance Thermometer	Prototype status	(2) Not recommended for SNAP-8 application
Pressure Sensor, Differential	(1)	Development status	Development program should be undertaken to satisfy SNAP-8 requirements
Pressure Sensor, Absolute	(1) Taylor Instruments P/N 706TN1103	Prototype status	Tested to 100 psi and 1400° F by ORNL with ±.5% accuracy. Adapt sensor to SNAP-8 requirements.
Flow Sensor, NaK	(1) Electromagnetic	Specific design units in use	Adapt design experience to SNAP-8 requirements.
Flow Sensor, Hg	(1) Electromagnetic	Development status	Adapt NaK flow sensor design to Hg loop.

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TABLE 3.3-1. INSTRUMENTATION AVAILABILITY (Cont'd)

FUNCTIONAL PART	POSSIBLE COMPONENT	KNOWN AVAILABILITY	CONSIDERATIONS
Level Sensor, Hg	(1) Resistance Bridge	Specific design units in use	Adapt design experience to SNAP-8 requirements.
	(2) Isotope Nuclear Gauge	Specific design units in use	Back-up design alternative.
Neutron Detector, Intermediate Range Full Power Range	(1) Compensated Ion Chamber GE Dwg. 104B1635	In stock	
	(2) Campbell detector	Development status	Back-up design alternative
Neutron Detector, Start-up Range	(1) Fission Counter GE Dwg. 104B1638	In stock	
Gamma Detector	(1) Gamma Ion Chamber GE Dwg. 104B1637	In stock	
Amplifier, Low Level	Fairchild Semi-Conductor Affiliate Development	Specific design units in use	Select or adapt units for SNAP-8 requirements.
Indicators, Temperature, Pressure, Flow, etc.		Design status, little progress toward spacecraft applications	Undertake development program to qualify visual display indicators for SNAP-8 environment.
Recorders, Multichannel		Pre-design status, little progress toward spacecraft applications.	Undertake development program to qualify recorders for SNAP-8 environment.

TABLE 3.3-1. INSTRUMENTATION AVAILABILITY (Cont'd)

FUNCTIONAL PART	POSSIBLE COMPONENT	KNOWN AVAILABILITY	CONSIDERATIONS
Amplifier, Analog Computational		Specific design units in use.	Select or adapt units for SNAP-8 requirements.
Position Sensor, Rotary	(1) LVDT (2) Potentiometer (3) Capacitance	Development status for rotary sensors. However, linear sensors are further developed and of simpler construction than rotary types.	Adapt linear displacement sensor if possible; otherwise develop rotary displacement sensor for SNAP-8 requirements.
Trip Circuit, High Threshold		Stock item	Select or adapt specific unit for SNAP-8 requirements
Trip Circuit, Low Threshold		Stock item	Select or adapt specific unit for SNAP-8 requirements

11. Temperature, Its Measurement and Control in Science and Industry, American Institute of Physics, Reinhold Publishing Company, Seventh Printing, 1958.

12. Dr. P. L. Studt et al., Bibliography on Liquid Metals Technology of Hg, Na and NaK, NASA Report 2550, Aerojet-General Corporation, September, 1963.

13. J. M. Harrer, Nuclear Reactor Control Engineering, D. VanNostrand Company, Inc., 1963.

14. P. J. Beneteau, "Drift Compensation in DC Amplifiers," Solid State Design, May 1964, p. 19-23.

15. David F. Hilbiber, "A New Transistor Differential Amplifier," IRE Transactions on Circuit Theory, December, 1961, p. 434-439.

3.4 GENERAL SPECIFICATIONS FOR INTEGRATION OF SNAP-8 NUCLEAR POWER SYSTEMS

In Appendix A of the Second Topical Report, preliminary specifications for the integration of a SNAP-8 power system with the three-spoke space station are included. Restraints for the initial and successive launch are defined. Review of those specifications upon completion of the study shows that no significant modification is required. However, certain of the specifications are relatively more significant and are important to the development of the SNAP-8 system dependent of the space station considered. These specifications that are of general importance are discussed here.

3.4.1. AUXILIARY POWER SOURCES

A. Station Activation Power

Highly reliable station activation power that is independent of the nuclear system will be required. It should be sized for minimum station checkout with the principal requirement being the checkout of the nuclear power system. It must include sufficient margin to allow for a change of power plants in the event that the first plant fails to start. The design should provide for regeneration of the activation power source after energy is available from the nuclear powerplant.

B. Auxiliary Power

Auxiliary power will be required during powerplant shut down or replacement and can include the activation power source discussed above. It should be sized to meet normal life support power requirements and essential mission objectives. The duration of the requirement is difficult to assess and is related to the time required to accomplish repairs, plant replacement, and start-up. The time for typical repairs and for start-up can be determined from tests performed on terrestrial plants. Plant replacement time can be determined from a detailed evaluation of the replacement operation with consideration of the experience obtained in early rendezvous and with due allowance for possible delays.

The duration requirement should be at least equal to the sum of the time necessary to accomplish the most sophisticated repair operation contemplated and the time required to replace, and start a powerplant, or the time required to replace and start two powerplants, whichever is greater. This will allow a plant to fail, a repair to be attempted, the repair to also fail, and the powerplant to be replaced. Or, it will allow a replacement to be attempted, the first attempt to fail, and the failed power plant to be replaced.

With the requirements suggested in these specifications:

- Replacement - 1 day,
- Start-up - 8 hours, and
- Maximum Repair Time - 2 days

the total time would be 3 days and 8 hours or 2 days and 16 hours.

C. Emergency Back-up Power

The emergency back-up power discussed in the Second Topical Report is judged to be not required since the auxiliary power discussed above will be sized to allow for failures in two independent powerplants before station auxiliary power is exhausted.

D. Last-Ditch Emergency

The last-ditch emergency power is required for crew escape and station de-activation. The power level and duration will be determined by the particulars of the mission and will be independent of the characteristics of the nuclear system.

3.4.2 STATION STABILITY AND BALANCE

The concentrated mass of the power system has a significant affect on the stability and balance of rotating space stations. The criteria is, of course, that the station must be balanced to rotate about its centerline and it must be sufficiently stable to be controlled. Balance can be obtained by the relative distribution of masses within the station; however, station usefulness can be seriously compromised as a result.

Considering stability, the powerplant will likely be located on the spin axis or in the spin plane. In the former case, the ratio of the moments of inertia may be less than 1.0 resulting in a more complex control system. In the latter case, the ratio will be greater than 1.0 resulting in a simpler control system. The relative plant positions can result in significantly different shield weights and therefore, a compromise between shield weight and control system complexity.

3.4.3 POWER PLANT OPERATION

A. Storage in Orbit

The initial powerplant will be stored in orbit for several days to months prior to start-up, depending upon the mission. Such storage is required to allow time for delays in rendezvousing with and in activating the station. This requirement will require modification of the present SNAP-8 start-up philosophy which relies upon preheat on the ground to prevent system freezing prior to start-up. Effective thermal shouds over the radiators to limit heat loss and auxiliary thermal energy will be required. Some flow will be required in the primary loop and in the heat rejection loops throughout the storage time.

The replacement powerplants will be stored in orbit for at least the lifetime of one plant. This will allow each plant to be brought into orbit one lifetime in advance to serve as a spare. A spare is thus available without the ground delays of preparing for launch and the logistics requirements are not increased because the same total number of plants are launched. Thermal shrouds are necessary over the radiators; however, auxiliary thermal energy will not be required as the waste heat from the station will be available.

B. Plant Start-up Time

A limitation on plant start-up time cannot be rigidly fixed. It must be short to mini-
mize the usage of auxiliary power, but it must be sufficiently long to allow a safe, ad-
equately checked start-up. The time must be less than "days" or otherwise, the weight
of the auxiliary power system will be exorbitant. The time cannot be less than "hours"
or there will be insufficient time for instrument checks and maintenance and for system
warm-up. The time of 8 hours for the initial start-up with two-men is suggested as a
reasonable compromise.

Two men are suggested because conditions may require one man to be in the powerplant
compartment and the second to be at the control console.

For other than the initial start-up, a lesser amount of time would be required and 5
hours with 2 men is suggested.

C. Number of Plant Shut-downs and Re-starts

The number of shut-downs and restarts must be limited because frequent shutdowns
are an indication of low reliability, cause an excessive usage of auxiliary power, and
require operator attention. Also, some techniques for preventing freeze-up of the
system radiators may utilize a limited supply of disposable thermal barriers that are
replaced at each shutdown. A requirement of not more than 4 shutdowns per year is
suggested.

D. Maintenance

All possible instruments, components, controls, and power conditioning equipment
should be located on the space station and be modular in design to allow for simple re-
placement. This has two benefits in that the equipment is readily accessible and it is
not replaced with the powerplant unless desired.

The remainder of the power system should be included in a sealable compartment to
allow normal access to the greatest possible fraction of the system components. All
maintenance to be accomplished on the system must be defined in advance and the ne-
cessary techniques developed. The time for various maintenance functions must be
defined and all maintenance requiring greater than a given time should be excluded

from consideration. Unlimited time is not available because of the limitations on auxiliary power and sufficient reserve must remain after maintenance to allow for powerplant replacement and start-up in the event that the maintenance is unsuccessful. A limiting maintenance time of two days is suggested.

3.4.4 POWERPLANT REPLACEMENT

A technique that allows for the replacement of completely assembled powerplants is a requirement. This will increase the reliability of replacement, minimize the demands on crew time, and minimize the time for replacement. A limiting replacement time of 1 day is suggested since the auxiliary power weight incurred is modest and it, in fact, appears practical to develop a replacement technique within that limitation.

3.4.5 CREW TIME FOR PLANT OPERATION AND MONITORING

The powerplant must be completely automated for start-up and operation to minimize the demands on crew time for operation and monitoring. Sufficient readouts and displays to allow the operator to observe the progress of start-up and operations will be necessary. The operator will be able to override the automatic system wherever necessary. It is difficult to establish firmly a limitation on crew time; however, it should be possible to provide a powerplant that will not require in excess of 4 man-hours/day average for monitoring, exclusive of maintenance operations.

4. SNAP-8 SYSTEM GROWTH POTENTIAL

As is common with most nuclear dynamic systems, the SNAP-8 Electrical Generating System incorporates significant design margin that can be used to provide power in excess of the nominal 35 KWe rating. The amount of additional power that can be obtained depends upon the performance of the individual components and the cycle in which the components are used. The component with the least growth potential will determine maximum output.

The design performance characteristics of the SNAP-8 components are used in this section to indicate maximum growth potential of a SNAP-8 Reactor coupled with single and parallel power conversion systems. As expected, with a single power conversion system, the components are the final limit on power; whereas, with parallel power conversion systems, the reactor is the final limit on power.

4.1 SNAP-8 REACTOR WITH SINGLE POWER CONVERSION SYSTEM

4.1.1 SNAP-8 REACTOR

The thermal reactor power required to obtain various net cycle output powers is shown in Figure 4.1-1. Values are shown for cycles that reject the shield cooling energy directly to space (without shield cooling) and for cycles that use the shield cooling energy in the power conversion loop (with shield cooling). Figure 4.1-1 shows that at the limiting published capability of 600 KWt, maximum net outputs of 57 and 65 KWe, respectively, may be obtained. The capability of the SNAP-8 Reactor for power above 600 KWt is classified and is discussed in the Classified Appendix.

The SNAP-8 Reactor is currently being tested and as of July 6, 1964, had attained the operating history summarized below.

SNAP-8 OPERATIONAL HOURS SUMMARY TO JULY 6, 1964

Temperature, °F	Hours at Given Power Level		Total Hours
	0 to 400 KWt	400 to 600 KWt	
1300	470	2550	3020
< 1300	1190	1040	2230
			5250 Hours

Total power generated in the same period was 1.85×10^6 KWt-hrs.

There is a relatively simple design modification that can be made in the reactor reflector that will result in a significant reduction in shield weight for manned stations. The reactor requires an envelope of 26 inch diameter whereas, the actual diameter of core plus reflector is only about 16 inches. The additional space is required to accommodate the out-swing of the reflector elements as shown in Figure 4.1-2.

The reflector elements are a source of scattered neutrons and must be shielded, thus requiring a 26-inch diameter shield envelope. This arrangement was chosen in the unmanned design to enhance the radiation cooling of the reflector cusps which are adjacent to the core. In the manned application, a shield cooling system will be necessary and the system can be used to provide active cooling to the cusps. In this case, a modified design, as shown in Figure 4.1-3, is possible.

The pivot point of the control elements is moved inward and the number of elements is increased; however, the number shown does not have any significance. The "flat" of each element is covered with a poison material to enhance the reactivity change between the "in" and "out" positions.

With this modification, the reactor envelope can be reduced from 26 inches to the range of 20 to 22 inches. For the shield described in detail in the Second Topical Report, Section 5.7 with a present weight of 20,200 pounds, the envelope reduction could reduce shield weight by 3000 to 5000 pounds.

4.1.2 PRIMARY NaK PMA

The required primary NaK PMA flow rate as a function of power level and boiler heat transfer capability is shown in Figure 4.1-1. The pressure drop characteristic for the primary loop is shown in Figure 4.1-4. This system characteristic is that which is obtained if the characteristic of the reactor is unmodified and the remainder of the loop (lines and boiler) is opened-up to maintain the same total pressure drop as the reference SNAP-8 system. The design head characteristic for the NaK PMA is shown dotted on Figure 4.1-4 for one pump and for two pumps in parallel. These data are used as follows to evaluate limiting power capability of the pump.

Figure 4.1-4 shows that a single pump will provide a flow of 45,000 lbs/hr without modification. This flow, per Figure 4.1-1, will allow a power between 40 and 50 KW

NET ELECTRICAL OUTPUT (kW$_e$)

MERCURY FLOW RATE
(LBS/HR x 10^{-3})

PRIMARY NaK FLOW RATE
(HRS/HR x 10^{-3})

UA OF Hg BOILER
% OF REFERENCE
DESIGN

200%
175%
150%
125%
100%

RADIATOR AREA
(FT^2)

RADIATOR LOOP
FLOW RATE = 54,000 LB/HR

CYCLE
EFFICIENCY (%)

REACTOR
POWER (KW)

WITH SHIELD COOLING

WITHOUT SHIELD COOLING
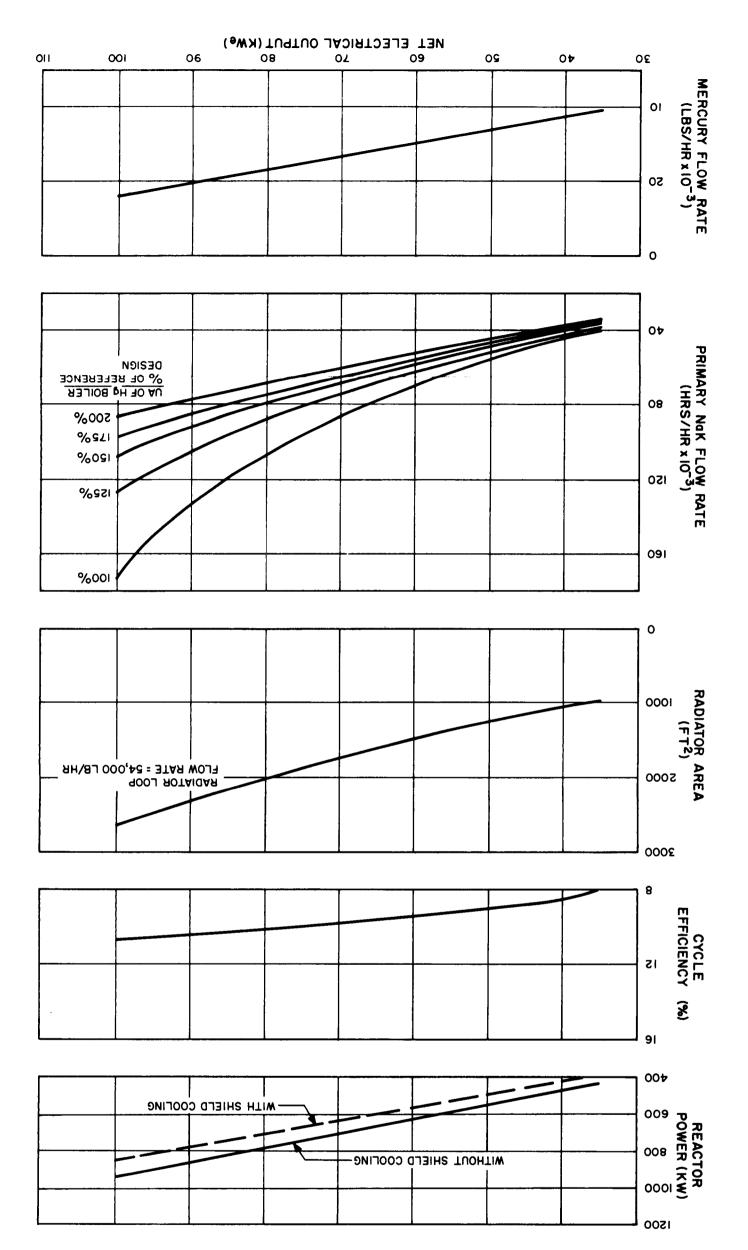
Figure 4.1-1. SNAP-8 Cycle Requirements
at Increased Net Power Output; One Power
Conversion System
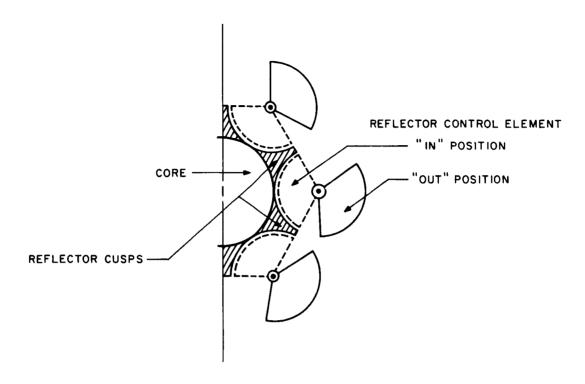
Figure 4.1-2. Present Reflector Control Drum Arrangement
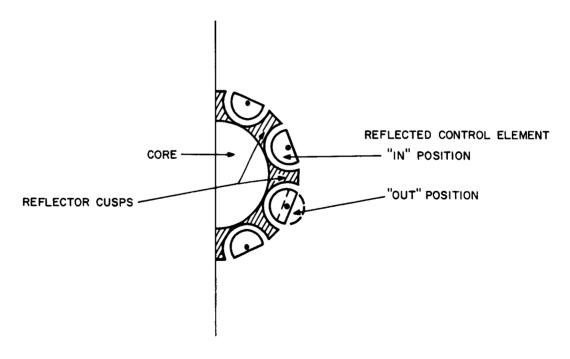
Figure 4.1-3. Modified Control Drum Arrangement
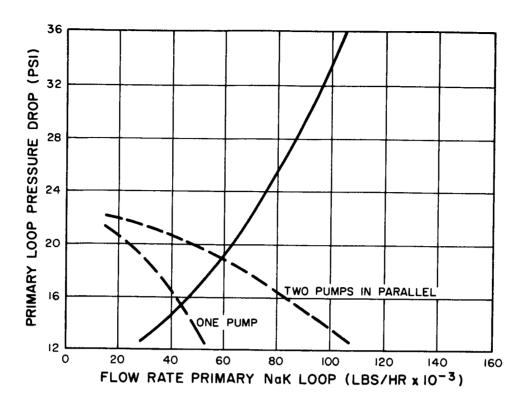
Figure 4.1-4. Primary Loop Pressure Drop vs. Flow Rate

depending upon the heat transfer capability of the boiler. The boiler UA is referenced to that required to meet the reference SNAP-8 cycle conditions. Since the boiler UA is not determined and in test, will likely be developed to exceed cycle requirements, it is concluded that one primary NaK PMA will be adequate for a power of 45 to 50 KWe.

Figure 4.1-4 shows that 2 pumps in parallel will provide a flow of 60,000 lb/hr, which per Figure 4.1-1, will allow a power output between 54 and 68 KW.

4.1.3 MERCURY-JET CENTRIFUGAL PMA

The required mercury flow rate as a function of power level is shown in Figure 4.1-1. If the loop line sizes, boiler and condenser shells are increased in proportion to the power level, then the required loop ΔP will remain constant at the present 355 psi. At such a differential pressure rise, Figure 4.1-5 shows that the Hg PMA can provide a flow rate of 16,000 lb/hr. This flow, per Figure 4.1-1, will allow a power output of 66 KW.
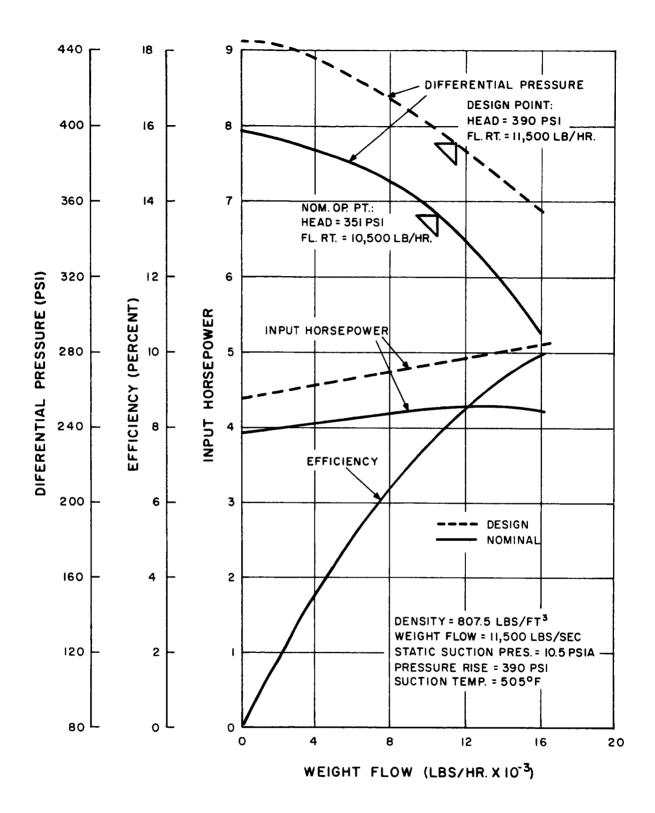
Figure 4.1-5. Anticipated Performance Curves; Hg-Jet/Centrifugal
Pump/Motor/Assembly

4.1.4 HEAT REJECTION LOOP NaK PMA

There is not a definite cut-off point in the usefulness of the HRL pump since its flow rate is of primary importance in determining the size of the primary radiator and radiator area can be accepted as a penalty for inadequate flow rate. The Second Topical Report, Figure 6.4-6, (page 6-56) showed a reduction in radiator area and weight for operation at a flow rate of 54,000 lb/hr (15 lb/sec) compared to the pump nominal flow of 36,700 lb/hr. This saving at a power level of 35 KWe is significant and it was assumed that the pump would, in fact, be operated at the higher flow rate. Figures 4.1-6 and 4.1-7 show a similar variation in radiator area with flow rate at power levels of 70 and 100 KWe, respectively. The parameter of condenser UA is included to show its relatively negligible effect on radiator area. The optimum pump flows are shown to be 85,000 lb/hr at 70 KW and 110,000 lb/hr at 100 KW. The negative slope of the curves below the optimum are an indication of the radiator weight penalty resulting from the non optimum flow rate. At 70 KW and 54,000 lb/hr, the slope is 11.5 ft^2 per 1000 lb/hr and since radiator total weight is approximately 3.7 lb/ft^2, the penalty for low flow rate is 42.5 lb per 1000 lb/hr. With the reference condenser, an increase in flow to optimum would reduce radiator area about 180 ft^2 and weight about 670 pounds.

At 100 KW and 54,000 lb/hr, the slope is even greater, resulting in a penalty of 95 lb per 1000 lb/hr. Again with the reference condenser, an increase in flow to optimum would reduce radiator area about 570 ft^2 and weight about 2100 pounds. Figure 4.1-8 shows the radiator weight penalty resulting from non-optimum flow rate as a function of power level. Two pumps in parallel can provide flows up to 100,000 pound/hr which would be adequate for power levels up to 100 KW.

4.1.5 MERCURY CONDENSER

The UA of the mercury condenser affects the required radiator area and HRL NaK flow rate. As shown in Figures 4.1-6 and 4.1-7, it is of little significance except at near optimum flow rates. Near these conditions, the greatest reduction in radiator area is obtained by a combined increase in flow rate and condenser UA. For instance, at 70 KW, area is reduced to 1570 ft^2 by a doubling of UA and a flow increase to 70,000 lb/hr; whereas, with the reference UA, a flow of 90,000 lb/hr is required to obtain the same radiator area.
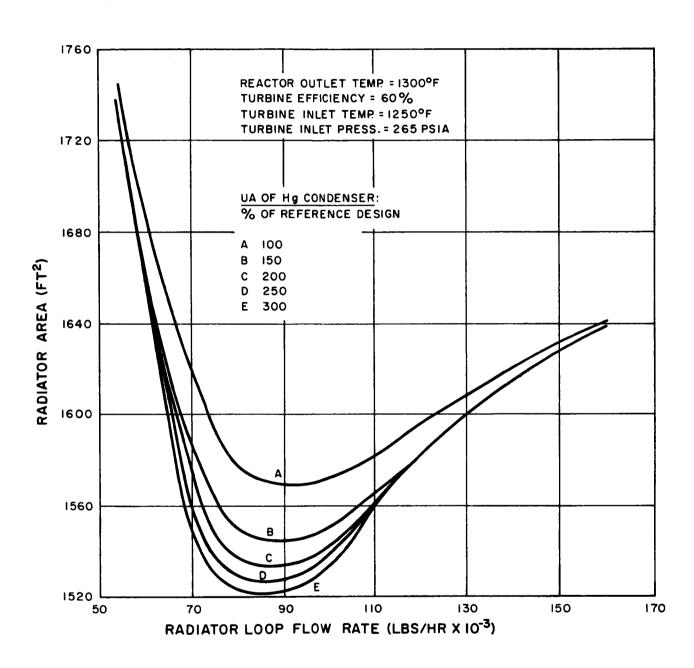
Figure 4.1-6. Radiator Area at 70 KWe; One Power Conversion System
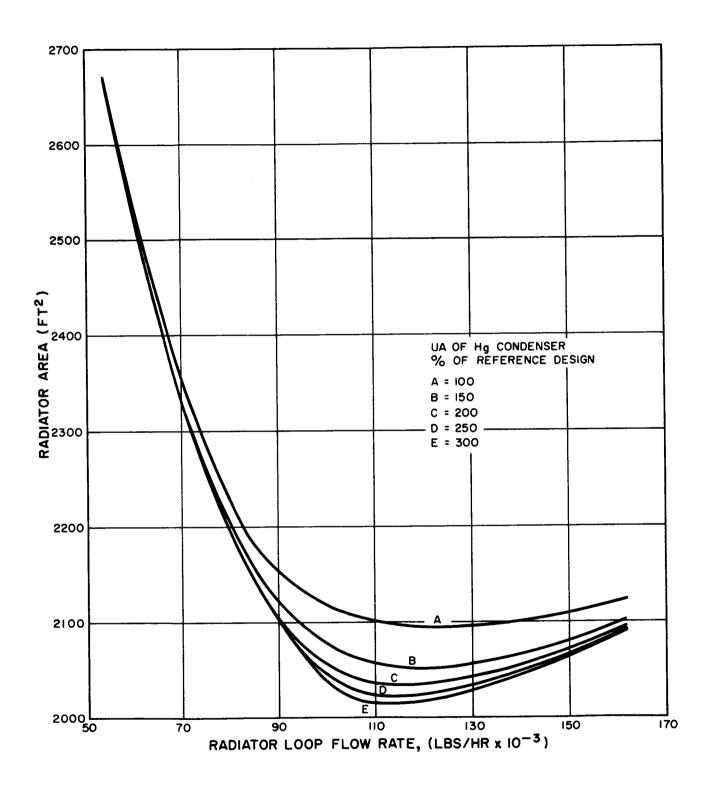
Figure 4.1-7. Radiator Area at 100 KWe; One Power Conversion System
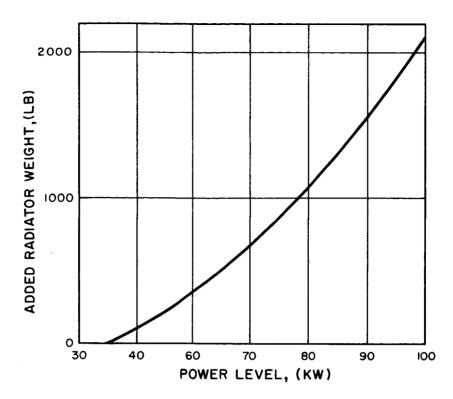
Figure 4.1-8. Radiator Weight Penalty (Reference Condenser)

4.1.6 MERCURY BOILER

The UA of the mercury boiler affects the required primary NaK flow rate significantly as shown in Figure 4.1-1. To provide for greater area, the length and the number of parallel tubes can be increased without changing the basic configuration or developing a new technology. Whether such an increase will, in fact, be required will be determined by the tests on the full size boiler which may in fact, have a UA greater than the reference value. A UA twice the reference value will be required to allow a single pump to provide sufficient flow for 50 KW. The flow rate is significantly affected by the UA because higher source temperatures and therefore higher flows are required to transfer additional heat as power is increased.

4.1.7 TURBINE - ALTERNATOR

The turbine is partial admission with the first two stages open 38%. Approximately 50% more power may be obtained with the opening-up of these stages. The first 20 to 30% increase over the design flow of 11,200 lb would in fact, be expected to result in an efficiency increase. Thus, flow could increase to 14,600 lb/hr with improved performance. Figure 4.1-2 shows that a power of 60 KW could be

obtained with this flow; however, 60 KW is not limiting for the turbine since significantly greater flow rates can be obtained.

The alternator will have a limiting output of about 60 KW total and since between 12 to 15 kw are used in pumps and controls, maximum alternator output will be from 45 to 48 KW net.

4.1.8 PRIMARY NaK HEAT REJECTION RADIATORS

The largest booster expected to be used with the SNAP-8 power plant is the Saturn IB. Its limiting payload envelope will provide a maximum fixed radiator area of about 2020 ft^2.

In a system that operates only one power conversion system, a redundant coolant-lube (secondary) radiator may be provided by including two sets of parallel tubes on the same radiator surface as discussed for the primary radiator in Phase II, Page 6-48. An area of 350 ft^2 is required for a coolant-lube radiator with a remainder of 1670 ft^2 for the primary radiator. Figure 4.1-1 indicates that a maximum power of 67 KW may be obtained with such an area. With increased loop flow Figure 4.1-6 indicates that power levels above 70 KW may be obtained.

4.1.9 SUMMARY - ONE POWER CONVERSION SYSTEM

The results obtained above are summarized in Figure 4.1-9 in a form to allow rapid assessment of SNAP-8 uprating capability. The end of the solid bar determines approximately the maximum capability of each major component; additional power will require a modified or new component. Figure 4.1-9 shows that:

- The boiler is apparently the first component to limit power. However, as discussed in Section 4.1-6, the heat transfer characteristic can only be determined by tests yet to be made and requirements will likely be exceeded. In any case, the boiler size may be increased as necessary to obtain additional heat transfer area and, therefore, power is not limited to 40 KWe.

- The alternator is the first component to truly restrict power level; the limiting power being about 48 KW.

- The other components also fail to meet requirements quickly thereafter and only the Hg pump and reactor are able to exceed 60 KWe.

#	COMPONENT	POWER LEVEL, KW$_E$	COMMENT
1.	REACTOR	(bar to ~65)	A POWER LEVEL OF 65 KW MAY BE OBTAINED AT A REACTOR POWER OF 600 KWT. ADDITIONAL CAPABILITY IS CLASSIFIED AND IS DISCUSSED IN CLASSIFIED APPENDIX A.
2.	PRIMARY NAK PMA	(bar to ~50, hatch to ~68)	ONE PUMP WILL PROVIDE SUFFICIENT FLOW FOR 50 KW. TWO PUMPS IN PARALLEL WILL PROVIDE ADDITIONAL FLOW TO ALLOW 68 KW. ABOVE 68 KW, A NEW PUMP WOULD BE REQUIRED.
3.	MERCURY-JET CENTRIFUGAL PMA	(bar to ~66)	
4.	HEAT REJECTION LOOP NAK PMA	(bar to ~60, hatch to ~100)	INADEQUATE FLOW IN THE RADIATOR LOOP RESULTS IN INCREASED RADIATOR SIZE AND WEIGHT. UP TO 60 KW, THE WEIGHT PENALTY IS ABOUT 400 POUNDS WHICH IS JUDGED ACCEPTABLE. TWO PUMPS IN PARALLEL WILL PROVIDE SUFFICIENT FLOW FOR POWER LEVELS UP TO 100 KW.
5.	MERCURY CONDENSER	(bar to ~60, hatch to ~100)	CONDENSER SIZE AFFECTS RADIATOR AREA AND RADIATOR FLOW RATE; HOWEVER NO SIGNIFICANT AFFECT IS APPARENT UNTIL LOOP FLOW RATE IS INCREASED TO OBTAIN MINIMUM RADIATOR AREA AT HIGHER POWER LEVELS. THE CONDENSER IS ADEQUATELY MATCHED TO THE PRESENT HRL NAK PUMP AND WILL NOT REQUIRE AN INCREASE IN SIZE UNLESS FLOW RATE IS INCREASED.
6.	MERCURY BOILER	(bar to ~40, hatch to ~100)	THE HEAT TRANSFER CHARACTERISTICS OF THE BOILER ARE PRESENTLY NOT DETERMINED. THE UA DEFINED BY REFERENCE CYCLE CONDITIONS WILL ALLOW A POWER OF 40 KW. BOILER SIZE (UA) MAY BE INCREASED AS NECESSARY TO OBTAIN ADDITIONAL POWER.
7.	TURBINE	(bar to ~75, hatch to ~100)	POWER OUTPUTS UP TO 60 KW MAY BE OBTAINED WITH A SLIGHT INCREASE IN EFFICIENCY BY OPENING UP THE FIRST TWO STAGES.
8.	ALTERNATOR	(bar to ~48)	LIMITING ALTERNATOR OUTPUT IS 60 KW BUT ABOUT 12 KW IS USED IN PUMPS, ETC., RESULTING IN 48 KW NET OUTPUT.
9.	RADIATOR AREA	(bar to ~70)	THE S1B BOOSTER CAN INCLUDE SUFFICIENT FIXED RADIATOR TO ATTAIN A POWER OF 70 KW. GREATER POWER WILL REQUIRE LARGER BOOSTER PAYLOAD ENVELOPES, HIGHER TEMPERATURE RADIATORS, OR FOLDING RADIATORS.

PRESENT DESIGN POINT

LEGEND

COMPONENT ADEQUATE WITHOUT MODIFICATION

COMPONENT ADEQUATE WITH MODIFICATION

NEW COMPONENT NECESSARY

Figure 4.1-9. SNAP-8 Up Rating Capability; One Power Conversion System

These analyses thus indicate that a SNAP-8 Reactor with a single power conversion system can provide at least 48 KWe without modification of the major components presently being developed.

4.2 SNAP-8 REACTOR AND PARALLEL POWER CONVERSION SYSTEMS

Previous studies (Phase II, Section 6.1) have shown a desirability for operation of two parallel power conversion systems at mercury loop temperature and pressures below those of the reference SNAP-8 cycle. At 35 KWe, optimum turbine inlet conditions are 200 psia and 1200°F and these conditions, with a maximum reactor outlet temperature of 1300°F, were used in evaluating system growth potential with parallel PCS's. However, there are optimum turbine inlet conditions at each power level that when determined, would provide power outputs slightly greater than predicted by this analysis at constant turbine inlet conditions.

4.2.1 SNAP-8 REACTOR
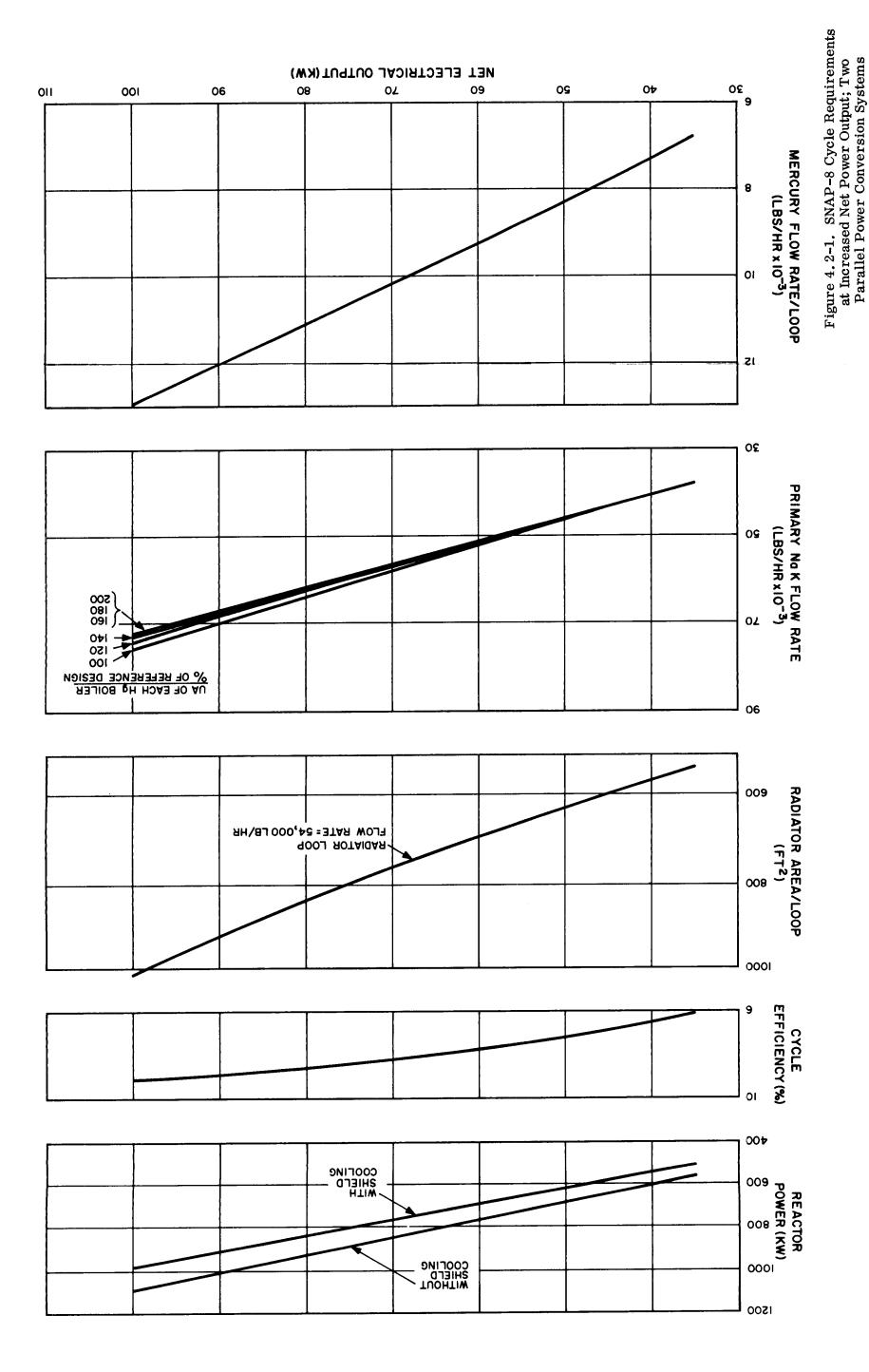
Operation of parallel PCS's results in a decreased cycle efficiency due to the additional electrical energy used in operating parallel controls, pumps, and turbine alternators. Greater reactor power is, therefore, required to produce a given output. Figure 4.2-1 shows that at 600 KWt, the maximum cycle output is 40 and 48 KWe, respectively, without and with shield cooling. Electrical output at higher reactor powers is discussed in the Classified Appendix.

4.2.2 PRIMARY NaK PMA

The required NaK flow rate shown in Figure 4.2-1 is relatively unaffected by the boiler UA and with the 60,000 lb/hr flow attainable with parallel PMA's, sufficient flow for a power of 77 KWe is provided.

4.2.3 MERCURY - JET CENTRIFUGAL PUMP

The required mercury flow rate per loop is less than design of 11,500 lb/hr up to power levels of 85 KW. At design differential pressure rise, the pump can provide 16,000 lb/hr as stated in Section 4.1.3 and this flow is greater than that required for 100 KW. Consequently, the mercury pump will not be limiting.

Figure 4.2-1. SNAP-8 Cycle Requirements
at Increased Net Power Output; Two
Parallel Power Conversion Systems

4.2.4 HEAT REJECTION LOOP NaK PMA

Figure 4.2-2 shows that at 35 KW the 54,000 lb/hr flow provided in each radiator loop is greater than required for minimum radiator area. The weight saving for reduced flow is about 6.1 pounds per 1000 lb/hr of coolant flow rate with the reference condenser and could be obtained by increasing loop resistance to decrease pump flow rate. The total gain to be attained is only 24 ft^2 per loop or 89 pounds per loop. Figure 4.2-3 shows that at 70 KWe, the pump flow rate of 54,000 lb/hr is practically optimum. Figure 4.2-4 shows that even up to power levels of 100 KW, the pump flow rate results in radiator areas close to optimum. With the reference condenser, the optimum radiator area is only 22 ft^2/loop (1010-988) lower than that at a flow rate of 54,000 lb/hr and would not warrant development of a new size of pump. Consequently, the heat rejection pumps will not require modification up to power levels of 100 KW.

4.2.5 MERCURY CONDENSER

The effect of condenser UA on radiator size and heat rejection loop flow rate is insignificant as shown in Figures 4.2-2 and 4.2-3 and 4.2-4. This is expected since each loop includes a full size condenser that at power levels below 70 KWe (twice 35 KWe), is actually transferring less than design heat.

4.2.6 MERCURY BOILER

The UA of the mercury boiler also has insignificant affect on the required primary NaK flow rate as shown in Figure 4.2-1. Again, this is as expected since the tube bundle transferring energy to each PCS loop has a heat transfer capability equal to that of the reference SNAP-8 boiler.

4.2.7 TURBINE ALTERNATOR

Parallel turbines with design flow of up to 11,200 lb/hr will provide a power output of 81 KWe and with slightly increased admission to the first two turbine stages, will provide greater than 100 KWe.

Each alternator is limited to 60 KW total output and with a total energy consumption of 25 to 30 KW within the cycle, a maximum output of 90 to 95 KWe net can be attained.
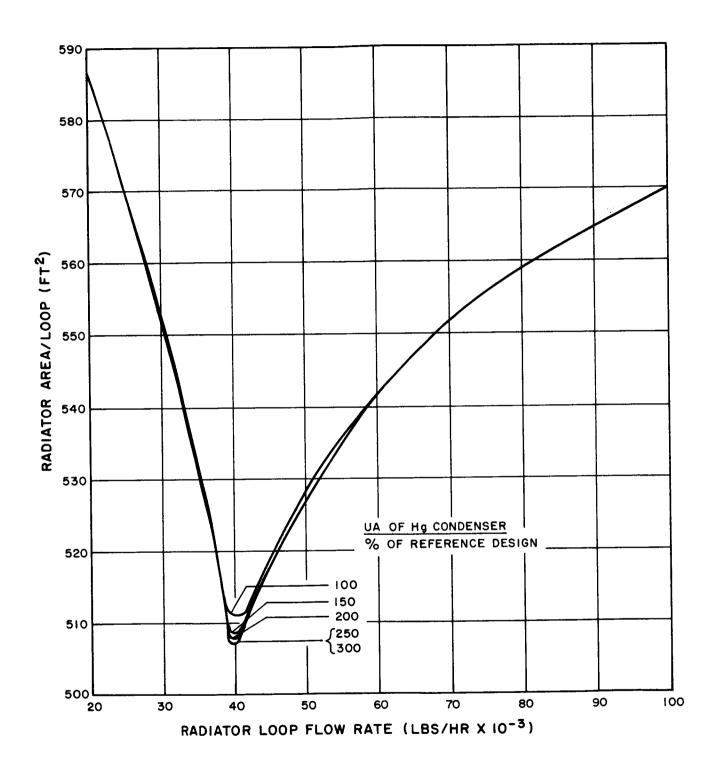
Figure 4.2-2. Radiator Area at 35 KWe; Two Parallel Power Conversion Systems

The chart axes and labels are:
- Y-axis: RADIATOR AREA/LOOP (FT^2), ranging from 500 to 590
- X-axis: RADIATOR LOOP FLOW RATE (LBS/HR X 10^{-3}), ranging from 20 to 100
- Legend: UA OF Hg CONDENSER / % OF REFERENCE DESIGN — 100, 150, 200, {250, 300}
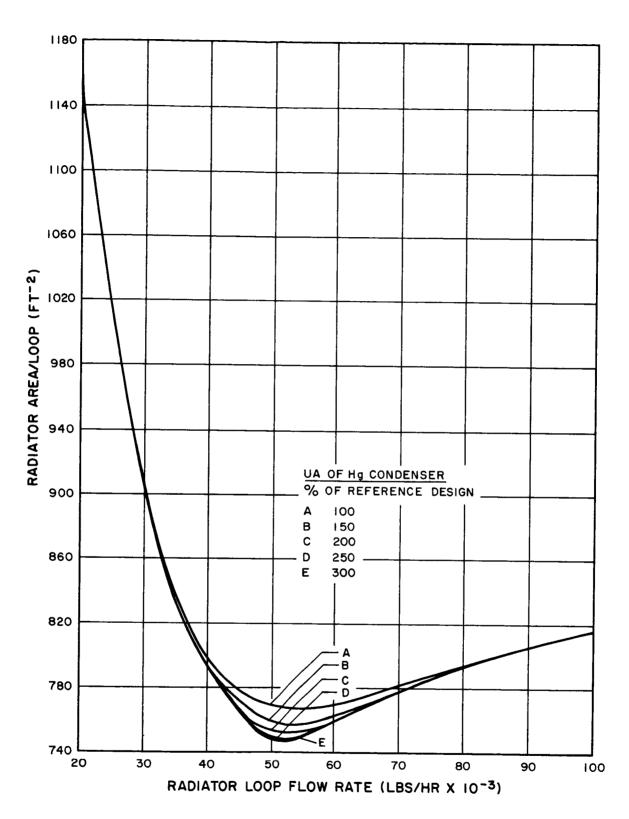
Figure 4.2-3. Radiator Area at 70 KWe; Two Parallel Power Conversion Systems
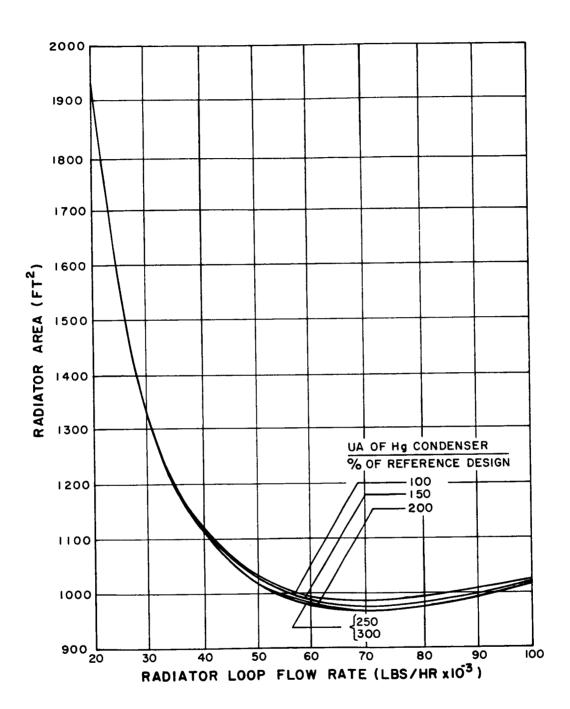
Figure 4.2-4. Radiator Area at 100 KWe; Two Parallel Power Conversion Systems

4.2.8 PRIMARY NaK HEAT REJECTION RADIATORS

With two power conversion systems operating in parallel, the heat rejected through the coolant-lube secondary radiators will be approximately doubled and the area required will be 700 ft^2 rather than 350° ft^2 as discussed in Section 4.1.8. With the maximum radiator area of 2020 ft^2 for the SIB, about 1320 ft^2 of area will be available for the two primary radiators or 660 ft^2 per loop. Figure 4.2-1 shows that a maximum power of 55 KWe can be obtained with such an area. Slightly greater power could be obtained by reductions of radiator area requirements through optimization of radiator loop flow rate and by increasing turbine back pressure; however, these changes would not likely result in a power significantly above 60 KW.

If a direct condensing radiator were developed, area requirements could be reduced approximately 22% and maximum power would be increased to about 75 KWe.

4.2.9 PARALLEL POWER CONVERSION SYSTEMS

The results obtained for a SNAP-8 Reactor with two parallel power conversion systems are shown in Figure 4.2-5. Only the reactor and the radiator area impose a limit on power in the range of interest.

- The reactor apparently restricts power to 48 KWe at a thermal power of 600 KWt, but with additional capability as discussed in the Classified Appendix, 48 KWe may be exceeded.
- The radiator area limit at 60 KWe is very real and significant system modifications are required in order to obtain additional power.

Comparison of the results obtained for single and parallel power conversion systems shows that both cycles are limited to about 48 KWe based upon the information given here. However, for a single PCS, the restriction is imposed by the limitations of the alternator which are definite. Whereas, for the parallel PCS's, the restriction is imposed by the design thermal power limitation of 600 KWt from the reactor. With increased thermal power available, parallel PCS's will be able to provide greater power without modification of system components than will a single PCS.

	COMPONENT	POWER LEVEL, KW$_E$	COMMENT
1.	REACTOR		A POWER LEVEL OF 48 KWE MAY BE OBTAINED AT A REACTOR POWER OF 600 KWT. ADDITIONAL CAPABILITY IS CLASSIFIED AND IS DISCUSSED IN CLASSIFIED APPENDIX A.
2.	PRIMARY NAK PUMP		PARALLEL PUMPS WILL PROVIDE SUFFICIENT FLOW FOR 77 KWE.
3.	MERCURY–JET CENTRIFUGAL PMA		PUMPS NOT LIMITING UP TO 100 KWE.
4.	HEAT REJECTION LOOP PMA		PUMPS NOT LIMITING UP TO 100 KWE.
5.	MERCURY CONDENSER		CONDENSERS NOT LIMITING UP TO 100 KWE.
6.	MERCURY BOILER		BOILERS NOT LIMITING UP TO 100 KWE.
7.	TURBINE		
8.	ALTERNATOR		NEW ALTERNATORS REQUIRED ABOVE 90 KWE.
9.	RADIATOR AREA		RADIATOR AREA LIMIT ON SIB BOOSTER RESTRICTS POWER TO 60 KWE.

Power level axis: 0 10 20 30 40 50 60 70 80 90 100

LEGEND

COMPONENT ADEQUATE WITHOUT MODIFICATION

COMPONENT ADEQUATE WITH MODIFICATION

NEW COMPONENT NECESSARY

PRESENT DESIGN POINT

Figure 4.2-5. SNAP-8 Up Rating Capability; Parallel Power Conversion Systems

5. COMPARISON OF SOLAR PHOTO-VOLTAIC AND SNAP-8 ELECTRIC POWER SYSTEMS

This section presents a comparison of solar photo-voltaic and SNAP-8 electric power systems for the three spoke station. Information on two solar photo-voltaic systems is provided. One system is described by the study performed by Lockheed Aircraft Corporation[1] for the station and the second is described by an independent study reported here-in. The information on SNAP-8 as modified and adapted for a manned application is taken from the I, II and III Topicals of this study. SNAP-8 systems that use chemical and electrical propulsion for station-keeping are included. The systems are compared at 40 KWe.

The comparison shows that the initial launch weights of solar photo-voltaic and SNAP-8 electric systems are comparable when the fuel requirements necessary to compensate for solar-array drag and orientation are included. Further, the yearly re-supply requirements for the nuclear system are about 7000 pounds lower due to decreased station fuel requirement.

5.1 40 KWe SOLAR PHOTO-VOLTAIC SYSTEM (GE STUDY)

This independent evaluation of a 40 KWe photo-voltaic system for the station used ground rules identical to those of the referenced Lockheed study, namely:

40 kw continuous power requirement

1968-1970 launch

260 n.mi. altitude

29-1/2° inclination

Up to 5-year mission

The photovoltaic power system will take the form shown in Figure 5.1-1, with efficiencies indicated. The power system consists of 6 identical sections, consistent with the philosophy in the Lockheed report.

SOLAR ARRAY

19,108 WATTS
42.2 VOLTS
452.8 AMPS

$\eta = .98$

41.4 VOLTS

$\eta = .99$

41.0 VOLTS

10,770 WATTS
41.0 VOLTS
262.7 AMPS

BATTERY CHARGE REGULATOR, INCLUDES AMP.- HR METER

$\eta = .94$

$\eta = .98$

10,124 WATTS   (7936 WATTS)   7794 WATTS   (7794 WATTS)
40.0 VOLTS   (38.6 VOLTS)   41.0 VOLTS   (33.0 VOLTS)
253.1 AMPS   (236.2 AMPS)   190.1 AMPS   (236.2 AMPS)

Ni-Cd BATTERY

VOLTAGE REGULATOR $\eta = .90$

7015 WATTS

4167 WATTS D.C   4209 WATTS   A
$\eta = .99$

2806 WATTS

2500 WATTS A.C   INVERTOR $\eta = .90$
$\eta = .99$

Figure 5.1-1. Solar Photo Voltaic Power Supply Subsystem; One System of Six

5.1.1 SOLAR ARRAY

The solar array uses N/P silicon solar cells 11% efficient to air mass zero solar radiation at 85°F. For study purposes 1 x 2 cm size cells are assumed, with an active area of 1.9 cm^2. (Lockheed: 10.15% at 28°C, corresponding to 10.08% at 85°F). Cells 10.5% efficient were available in 1963 in high production yields, and since cells for 1968 launch will not be produced until late 1966 and 1967, a minor improvement in cell efficiency may be postulated in the interim.

The following loss factors are reasonable:

1.	Soldering and other manufacturing processes	0.97
2.	Attenuation of output by cones, glass, and filter	0.92
3.	Micrometeorite erosion ultraviolet degradation and random cell failures	0.95
4.	Annual variation in solar constant	0.966
5.	Orientation (±10 degrees)	0.985
6.	Lumped measurement uncertainties	0.96
7.	Temperature effects, relative to output at 85°F	-0.26% per degree F

Calculations (Ref. 2) show that for N/P solar cells with 6-mil cover glass, no measurable radiation degradation will occur in 260 n. mi. orbits with inclination up to 60 degrees, for periods as long as 5 years, and, therefore, no radiation degradation factor is included.

The temperature of the solar cells, with blue-red filter optimized for use with N/P solar cells, is estimated to be 121°F, using average values of albedo and earth radiation flux, and typical vehicle reflection and radiation heating values. (Lockheed 125.6°F). The resultant power output is calculated to be 10.05 watts per square foot of active solar cell area.

The gross area of a solar panel will depend on the type of cell arrangement, panel construction, etc. A packing factor of 0.9 is assumed as being typical of that attainable with reasonable effort. The packing factor is defined as the ratio of the net active solar cell area to the gross area of the solar cell panel.

The unit area weight also is a function of solar panel design and arrangement. W. Cherry (Ref. 3) reports panel weights ranging from 1.19 to 1.63 lb/ft^2 for fixed solar panels in smaller sizes (1 kw or less). Studies on other programs of solar panels in the size range considered here, show that a weight of 1.4 lb per sq. ft. of active solar cell area is typical of that which can be obtained through good quality engineering effort. This specific weight includes the following:

Module Components:

- Solar Cells
- 0.006 in. glass covers with filters
- Glass-to-cell adhesive
- Cell-to-substrate adhesive
- Electrical insulation between cells and substrate
- Aluminum honeycomb substrate
- Paint
- Wire
- Solder
- Terminals
- Diodes

Frame Components:

- Frame
- Hinges
- Tie downs
- Deployment mechanisms

5.1.2 BATTERY

The batteries consist of nickel-cadmium cells, charged using a two-step charge method. (Lockheed: silver-cadmium). Silver-cadmium batteries do not presently have the cycle life required at reasonable depths of discharge (Ref. 4), and, unless a major breakthrough occurs, will not have by the projected launch date (Ref. 5).

When operating a nickel-cadmium battery through a large number of charge-discharge cycles, an excess number of ampere-hours must be placed into the battery during each charge cycle in order to fully restore the battery and prevent a decline in the battery capacity. At the charging rates to be considered for this application, the required overcharge amounts to 25 percent. During the overcharge condition, the current must be limited, since the oxygen recombination rate is naturally limited, and because, in overcharge, all the energy placed into the battery is converted to heat, which must be removed. The maximum usable overcharge rate is the 6-hour rate (that rate which would return all the current to the battery in 6 hours).

For many spacecraft applications, Ni-Cd batteries are recycled under constant-current charging conditions. Since the overcharge current must be limited, the charge current is limited also, and this essentially determines the size of the battery. For this application, for instance, the 6-hour charge rate will limit the maximum depth of discharge to about 13 percent.

A two-step constant-current charging method charges the batteries at a high constant current rate until the capacity previously removed has been replaced. During the following overcharge period, the rate is lowered radically so that heat and gas generation is considerably reduced. This method requires an increase in size of the solar array, but results in a large reduction in size of the battery required.

The two-step charge method requires some means to determine when 100 percent of the charge has been returned to the battery. The only practical means to determine this is an ampere-hour meter, which may be a unit-similar to the one proposed by Lockheed. Such a unit is included in the battery charge control.

The specific energy density for nickel-cadmium batteries in the large sizes to be utilized for this application is expected to be approximately 12 watt-hours per pound (Ref 5) (Lockheed: 15.6 w-hr/lb. for Ag-Cd). This weight will include the cells, internal connections, potting, case, mounting brackets, and connectors.

5.1.3 TWO-STEP BATTERY CHARGE

The two-step charge requires an increase in the size of the solar array, but permits a decrease in battery size. Examination of the Figure 5.1-2 will show the relation between maximum battery charge rate and the increase in solar array power required for charging.
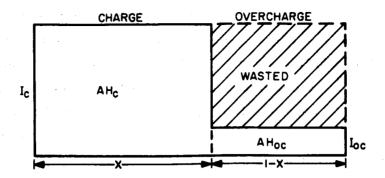
Figure 5.1-2. Relation Between Maximum Battery Charge Rate
and Increase in Solar Array Power

$$I_c = \text{Normalized Charge current} = \frac{1}{\text{charge rate (hours)}}$$

$$I_{oc} = \text{Normalized overcharge current} = \frac{1}{\text{overcharge rate}} = \frac{1}{6}$$

$$AH_c = \text{Normalized Ampere-hours charge}$$

$$AH_{oc} = \text{Normalized Ampere-hours of overcharge} = 0.25\, AH_c$$

$$X = \text{Relative time required to return full charge to the battery}$$

$$XI_c = 4(1-X)\, I_{oc}$$

$$XI_c = \frac{2}{3}(1-X)$$

$$X = \frac{1}{1 + \dfrac{3I_c}{2}}$$

UF = Array and battery utilization factor, the efficiency with which that portion
of the solar array "assigned" to battery charging is used. The "battery"
portion of the solar array must be made larger by 1/UF to supply the re-
quired charging.

$$UF = \frac{1.25 \times I_c}{I_c}$$

$$UF = 1.25X$$

MF = array multiplication factor, that factor by which the entire solar array
must be made larger to account for inefficient usage by the two-step
charge method.

Since it will be developed that the array power required for charging the battery, using the 6-hour constant-current charge, will be almost exactly equal to that power required to supply the continuous power requirements when the spacecraft is in the sunlight, the array multiplication factor may be closely approximated as:

$$MF = \frac{1 + \frac{1}{UF}}{2}$$

The following factors result:

Charge Rate, Hours	UF	$\frac{1}{UF}$	MF
1.5	.625	1.6	1.3
2	.714	1.4	1.2
3	.833	1.2	1.1
4	.901	1.1	1.05
6	1.0	1.0	1.0

5.1.4 POWER CONDITIONING EQUIPMENT

The power conditioning equipment types required will be similar to those specified by Lockheed.

Invertor — The efficiency (90%) and specific weights (20 lb/kw) given by Lockheed, for this function are typical of the performance that can be obtained in this time period, and are used.

Voltage Regulator — Evaluation of pulse-width modulation techniques indicate an efficiency of 90% (Lockheed: 93%) and a specific weight of 15 lb/kw (Lockheed: 3.4 lb/kw) are the best performance that can realistically be obtained in the projected time period. The heavier weight is necessitated by the output filtering required in order to meet the ±0.5 volt regulation specified.

Battery Charge Regulator — This unit will be a pulse-width-modulated switch, but output filtering will not be required, since the battery itself acts as a large filter. Efficiency as high as 94% (Lockheed: 93%) has been achieved in flight-qualified hardware, and a specific weight of 4 lb/kw (Lockheed: 3.4 lb/kw) will be used.

Ampere-Hour Meter — This will be required in order to sense the state-of-charge of the battery, and control the battery charge current reference for the battery charge regulator. A weight of 5 lb will be used, as indicated for the Culton unit.

5.1.5 POWER SUPPLY HARNESS

A harness is required to collect the power from the solar array and distribute it within the power subsystem. A specific weight for this harness, based on Advent and other programs, is 13 lb/kw of solar array power (Ref. 2).

The voltage drop through the power supply harness will result in a harness loss factor of 0.99. A similar loss may be expected in the power distribution harness.

5.1.6 SOLAR ARRAY SIZING

The solar array size, for constant current battery charging, will be:

$$P_{SA} = \frac{1}{Z} P_C + \frac{T_D}{\eta_e T_L} P_C$$

where:

P_{SA} = Solar array power

P_C = Continuous power requirements

Z = Product of loss factors:

   Array diodes
   Harnesses
   Voltage regulator

η_e = Total power efficiency through battery, includes Z plus:

   Battery charge control
   Battery charge – discharge efficiency
   Battery isolation diode

T_D = Orbit shadow time

T_L = Light time

The system will be sized to the power demand at point A in Figure 5.1-1.

The first term in the above expression is the continuous daylight power term, and the second is the battery charging term.

5-8

The loss coefficients (referring to Figure 5.1-1) are:

$$Z = .98\ (.99)\ (.90) = .873$$

$$\eta_e = .873\ (.94)\ (.67)\ (.98) = .539$$

For a 260 n.mi. orbit,

$$T_D = 35.83\ \text{min.}\ \text{(Lockheed: 36 min.)}$$

$$T_L = 58.51\ \text{min.}\ \text{(Lockheed: 56 min.)}$$

So:

$$P_{SA} = 1.145\ P_C + 1.136\ P_c = 2.281\ P_c.$$

Note that the first term, the continuous daylight power term, is almost exactly equal to the second term, the battery charging power term.

From Figure 5.1-1, $P_c = 7.015$ kw

$$P_{SA} = 16.0\ \text{kw per section}$$

The net solar cell area required per section is:

$$\text{Area} = \frac{16.0}{10.05} = 1592\ \text{ft}^2$$

The panel weight per section is:

$$1592\ (1.4) = 2230\ \text{lb.}$$

The solar array weight for the entire vehicle is 13,370 lb.

When a two-step battery charge is used, the batter charging term ($\frac{T_D}{\eta_e T_L}\ P_C$) must be increased by the factor 1/UF, as discussed previously, or, for simplicity, the array power and weight may be increased by the array multiplication factor.

5.1.7 BATTERY SIZING

The battery is sized by the maximum charging rate. The battery charging current is:

$$I_c = \frac{1}{V_c} \, \eta_{BCR} \, \eta_H \, \eta_D \, \frac{1}{UF} \, \frac{T_d}{\eta_e T_L} \, P_c$$

Where:

V_c = Average battery charge voltage

η_{BCR} = Battery charge regulator efficiency

η_H = Array harness loss factor

η_D = Diode loss factor

The battery capacity, in ampere-hours, will be the charge rate multiplied by the charging current:

$$C_{AH} = CR \, (I_c)$$

$$CR = \text{Battery charging rate in hours}$$

The voltage drop through an efficiently-designed switching buck regulator will be approximately 1 volt, and there will be about 0.6 volt drop through the battery blocking diode. Therefore, the voltage regulator must see an input of 29.6 volts or higher. At an end-of-discharge voltage of 1.1 volts per cell, 27 cells will be required. The battery will use 28 cells (one additional for voltage margin). The following voltage range will result:

	Cell	Battery
Average discharge voltage	1.2 v	33.6 v
Average charge voltage (V_c)	1.43 v	4.0 v

Using the loss factors from Figure 5.1-1, and other previously developed values, the battery ampere-hour capacity may be expressed:

$$C_{AH} = .0259 \, \frac{C.R.}{UF} \, P_c$$

5.1.8 BATTERY CHARGE RATE TRADE OFF

As indicated earlier, adoption of a two-step battery charge method will result in a lighter battery and a heavier solar array. There is a trade off, then, between the battery and the array weight to find the optimum battery charge rate (defined as that weight resulting in the lightest power supply weight). The numerical development of this tradeoff is shown in Table 5.1-1, where the major power subsystem components dependent on the trade-off are sized using the criteria and methods developed previously.

TABLE 5.1-1. TRADE-OFF DEPENDENCE ON BATTERY CHARGE RATE

Charge rate	1.5	2	3	4	6
$\frac{1}{UF}$	1.6	1.4	1.2	1.1	1.0
Battery, capacity per section, amp-hr.	435	508	653	798	1088
Depth-of-discharge, percent	32.5	27.9	21.7	17.7	13.0
Watt-hr per section	14,620	17,070	21,940	26,800	36,550
Battery weight, per section, lb.	1218	1423	1828	2235	3046
Total Battery Wt., lb.	7308	8538	10,970	13,420	18,270
Battery Life (Ref. 4) Cycles	7510	7990	8620	9050	9600
Years	1.348	1.435	1.547	1.625	1.724
Yearly battery re-supply, lb.	5420	5950	7090		
Array Multiplication Factor, MF	1.3	1.2	1.1	1.05	1.0
Array weight (Approx.)	17,380	16,040	14,710	14,040	13,370
Battery Charge Reg., lb.	274	240	206	188	171
Power Supply Hanress, lb.	1608	1485	1361	1300	1238
Initial Launch Weight, lb.	26,570	26,303	27,247	28,948	33,049

The 2-hour charge rate is used. The apparent 530 lb. per year resupply advantage for the 1.5-hour charge rate is offset in large part by the additional propellant requirements for the larger solar array. The additional 1340 lb of solar array corresponds to approximately 1065 ft^2 of gross solar array, which will require approximately an additional 460 lb. of propellant yearly. Further, pushing the battery to a 1 1/2-hour charge rate, while it can be done, creates high thermal stresses in the battery, and increases the battery cooling requirements. Furthermore, the voltage will rise so high that the charge rate must be reduced before 100% of charge is returned to the battery, thus reducing the charge efficiency and increasing the solar array size even further than indicated in Table 5.1-1 (Ref. 5).

5.1.9 POWER CONDITIONING EQUIPMENT SIZING.

The power conditioning equipment required per section is:

- Invertor   50 lb   2160 in.^{3}
- Battery Charge Regulator
  and Ampere-Hour Meter   45 lb   1300 in.^{3}
- Voltage Regulator   105 lb   3030 in.^{3}
- 6 Sections   1200 lb   39,000 in.^{3}
- Array Monitor   10 lb
- Misc. Panels, Relays,
  Diodes, etc.   240
- Total   1450 per vehicle

5.1.10 BATTERY COOLING REQUIREMENTS

The average battery heating rate is determined from the average charge-discharge efficiency and the battery discharge. The battery discharge is 7936 (35.83/60) = 4739 watt-hours per section so, $\frac{1 - .67}{.67}$ (4739) = 2333 watt-hours of heat is generated each cycle, or an average of 2.4 kw. The entire power supply will generate an average of 14.4 kw of heat.

Earlier studies on skin-mounted low-temperature radiators indicated a specific weight of 40 lb per kw of heat rejected. Thus, the battery cooling system will weigh approximately 576 lb.

5.1.11 WEIGHT SUMMARY

A summary of the power supply weights derived is presented in Table 5.1-2. Not included are allowances for yearly resupply of power conditioning equipment, solar arrays, or propulsion fuel penalty.

TABLE 5.1-2. DATA SUMMARY, 40 KWe SOLAR PHOTO-VOLTAIC POWER SUBSYSTEM

Number of sections in power supply	6
Solar cell	N/P
Efficiency at 85° F, AMO	11.0%
Cover glass thickness	6 mils
Array weight per unit active area	1.4 lb/ft^2
Battery capacity per section	510 amp-hr
Battery type	Nickel-Cadmium
Solar array power per section	19,108 w
Array power output per unit active cell area	10.05 w/ft^2
Net solar cell area per section	1902 ft^2
Gross solar array area per section	2113 ft^2
Total gross solar array area	$12,678 \text{ ft}^2$
Solar Cells	5,580,000
Array weight	15,980 lb
Battery weight	8538 lb
spares	1423 lb
Total battery weight	9961 lb
Power conditioning & control equip.	1450 lb
Power supply harness	1490 lb
Battery cooling system	576 lb
Auxiliary power supply	490 lb
Total power supply at launch	29,947 lb
Yearly resupply Batteries	5950

5.1.12 COST OF POWER SUPPLY

The cost of a solar photovoltaic power supply is generally based on the number of solar cells, since the cost of the battery, regulators, etc. is generally smaller than the uncertainties in the estimates. Cost improvements in large arrays can be expected.

Installed costs as low as $5 per cell have been mentioned in meetings. This figure was quoted by Mr. Byers of Chance Vought at a Solar Dynamic Symposium in Washington, D.C. in September of 1963. This figure was supported by Walter Scott of NASA, with the condition that the government standardize specs and procurement procedures and quantities, as being applicable to power supplies in the range of 40 kw.

A more conservative figure for the near future might be $8 a cell. Thus, the cost of this 40 kw power supply will be about $28 million to $45 million.

5.2 40 KWe SOLAR PHOTO-VOLTAIC SYSTEM (LOCKHEED STUDY)

The details of the system are described in the referenced reports (Ref. 1). The initial launch weight for the system is given in Table 5.2-1 as 22,150 pounds. The GE study indicates by comparison a launch weight of 29,747 pounds. The weight difference is prinicpally a result of differences in battery weights. The Lockheed study used Ag-Cd batteries that will require development to meet the goals on cycle lifetime; whereas, the GE study used Ni-Cd batteries that are somewhat heavier but have better cycle lifetime characteristics.

5.3 SNAP-8 POWER SYSTEM

The initial launch weights for 40 and 47.5 KW SNAP-8 power systems are given in Table 5.3-1. The 47.5 KW system is presented to show a typical advantage of using electrical power to perform a task presently accomplished by other means. As discussed in Phase II, Section 7.2, electric propulsion can be used for normal station keeping (e.g., overcome drag, spin maintenance, station orientation) to reduce station fuel requirements by a factor of 3.5 to 4. If a pulsed arc-jet requiring 35 KW is used for propulsion, the power system output must be increased 7.5 KW. The 7.5 KW is used to charge a set of batteries which are discharged at a 27.5 KW rate. The 27.5 KW from the batteries plus the 7.5 KW from the reactor provide the pulse power to the arc-jet. Discharge and charge time will be about 3 and 14 minutes, respectively. Depth of

TABLE 5.2-1. INITIAL LAUNCH WEIGHT FOR 40 KWe SOLAR-PHOTO VOLTAIC SYSTEM (LOCKHEED STUDY)

	Pounds
Basic System	20,150
Spare Batteries	900
Spare Solar Arrays	400
Pre-Deployment Power	500
Battery Cooling System and Radiator	200
Total	22,150

TABLE 5.3-1. INITIAL LAUNCH WEIGHT FOR SNAP-8 NUCLEAR SYSTEM

	Without Electric Propulsion (lbs)	With Electric Propulsion (lbs)
Power Level	40	47.5
Reactor, lbs	540	540
Shield****	20,200	20,200
Shield Cooling System	100	100
Shield Support Structure	300	300
Primary Radiators (2)*	4,000	4,750
Secondary Radiators (2)*	1,700	1,700
Power Conversion System**	3,600	3,600
Power Conversion Structure	350	350
Boom Structure	1,800	1,800
Deployment System	500	500
Sub Total for SNAP-8 Nuclear Plant	33,090	33,840
Auxiliary Power (H_2 - O_2 Fuel Cells)	6,090	6,090
Storage Batteries for *** Electric Propulsion		980
Total Weight	39,180 lbs	40,910 lbs

     * Includes Structure
   ** Includes redundancy
  *** Includes controls and structures
**** Shield does not vary as shield is designed for 600 KWt thermal limit of reactor.

discharge is 10% and battery plus control system weight is 980 pounds. Battery life-time is one year.

The weight of the nuclear systems at 40 to 4.75 KW does not change except in primary radiator weight. The radiator is increased in proportion to output. Shield weight does not vary because the shield is sized based upon a reactor power level of 600 KWt which is adequate for both power levels.

Back-up power in the form of H_2-O_2 fuel cells are included for pre-station activation power, auxiliary power, and "last-ditch" emergency escape power. The level and duration of the power is respectively, 2 KWe for 50 hours, 14 KWe for 120 hours, and 4 KWe for 72 hours.

5.4 STATION FUEL REQUIREMENTS

The yearly fuel requirements for the station are given in Table 5.4-1. The solar systems require additional fuel for attitude control and orbit maintenance and in, the Lockheed study, (Ref. 1 and 6), 2950 and 4560 pounds are attributed to these causes, respectively. The additional fuel required due to the larger solar arrays in the GE study is calculated at 0.00128 lbs/day-ft^2. The fuel is N_2O_4/(50-50) UDMH - N_2H_4.

The nuclear systems present some drag and the necessary fuel is included for orbit maintaining. With electric propulsion, either ammonia or hydrogen may be used as the fuel.

5.5 POWER SYSTEM INITIAL LAUNCH WEIGHTS

The initial launch weights for the systems are summarized in Table 5.5-1 including the station fuel requirements for one year. As shown, the large fuel requirements of the solar systems offsets their apparent weight advantage and results in initial launch weights that are essentially equivalent. A time period of one year is chosen for the fuel requirements because the nuclear system and the solar system batteries are expected to both require replacement at about one year. Longer time periods will show the solar systems at a disadvantage. A shorter time will decrease solar system initial launch weight but it will increase the re-supply requirements which are more costly on a per pound basis and, therefore, show an even greater disadvantage.

TABLE 5.4-1. STATION YEARLY FUEL REQUIREMENTS

	40 KWe Solar Photo-Voltaic		40 KWe Man-Rated SNAP-8	
	Power System Study LR-17228 (Lockheed)	Power System Study (GE)	Without Electric Propulsion	With Electric Propulsion
Attitude Control, lbs	5,450	5,450	2,500	725
Spin Maintenance and Emergency Stabilization, lbs	675	675	675	195
Orbit Maintaining, lbs	9,150	10,510	4,810	1,330
Total	15,275 lbs	16,635 lbs	7,985 lbs	2,250 lbs

TABLE 5.5-1. INITIAL LAUNCH WEIGHT OF SOLAR CELL AND NUCLEAR SYSTEMS (40 KWe)

	Solar Photo-Voltaic		Man Rated SNAP-8**	
	Power System Study (Lockheed)	Power System Study (GE)	Without Electric Propulsion	With Electric* Propulsion
Power System, lbs	22,150	29,950	39,180	40,910
Fuel (one year), lbs	15,275	16,635	7,985	2,250
Support Structure and Tankage for fuel, lbs	2,110	2,300	1,100	230
Total	39,535 lbs	48,885 lbs	48,265 lbs	43,390 lbs

** Includes 6087 pounds for H_2 - O_2 Fuel cell as auxiliary power
* Must generate 47.5 KWe to provide 7.5 KW average for electric propulsion

5.6 SOLAR PHOTO-VOLTAIC SYSTEM REPLACEMENT WEIGHT

The yearly replacement weights for the solar photo-voltaic systems is shown in Table 5.6-1. The Ag-Cd batteries in the Lockheed study are predicted to have a lifetime of about one year at the particular duty conditions and, therefore, replacement of a full set is required each year. The Ni-Cd batteries weigh more (8538 pounds compared to 5820 pounds); however, the lifetime is expected to be 1.43 years and the re-supply is 5950 pounds/year. A weight equal to 10% of the weight of the batteries plus the spares is included to account for the tie-down and support structure on the re-supply booster.

TABLE 5.6-1. YEARLY REPLACEMENT WEIGHT FOR SOLAR
PHOTO-VOLTAIC SYSTEMS (40 KWe)

	Power System Study (Lockheed)	Power System Study (GE)
Batteries, lbs	5,820	5,950
Power Conditioning, Spares, lbs	350	350
Structure (10%), lbs	620	630
Total	6,790 lbs	6,930 lbs

5.7 SNAP-8 SYSTEM REPLACEMENT WEIGHT

The weights for the replacement SNAP-8 units are given in Table 5.7-1. Primary radiator weight is greater than on the initial unit because additional structure is required to stiffen the radiator for launch with loads in compression. (In the initial launch the radiator is in tension because the powerplant is in an inverted position from that of the replacement launches). A weight of 1000 pounds is included for the propulsion unit that will be used in the disposal of the old reactor. Batteries are included in the electric propulsion case.

5.8 POWER SYSTEMS RE-SUPPLY REQUIREMENTS

The yearly re-supply requirements for the solar photo-voltaic and SNAP-8 systems are shown in Table 5.8-1. As was done for the battery weights, the SNAP-8 weights are reduced by 1.14 to account for its greater than 1-year lifetime (10,000 hours).

TABLE 5.7-1. WEIGHT OF SNAP-8 REPLACEMENT POWERPLANT

	Without Electric Propulsion 40 KW (lbs)	With Electric Propulsion 47.5 KW (lbs)
Reactor	540	540
Replaceable Shield Section	3,100	3,100
Shield Cooling System	100	100
Shield Support Structure	300	300
Primary Radiators * (2)	4,260	5,070
Secondary Radiators **	940	940
Power Conversion System ***	3,600	3,600
Power Conversion Structure	350	350
Radiator Thermal Shroud	660	790
Sub-Total for SNAP-8 Nuclear Plant	13,850	14,790
Disposal Propulsion Unit	1,000	1,000
Batteries		980
Total Replacement Weight	14,850 lbs	16,770 lbs

   * Includes structure
  ** 50% of secondary radiator weight is allocated to other re-supply stores which it supports at launch
 *** Includes redundancy

As shown, the net re-supply requirements for the SNAP-8 systems are lower than those of the solar systems, particularly, if electric propulsion is used to further reduce the station fuel requirements. With a minimum re-supply cost of $1000/lb of the SIB vehicle, the 7000 pound weight differential will result in a program saving of about $7,000,000/year for each station with SNAP-8.

The effect of initial and re-supply weight is shown in Figure 5.8-1 where the cumulative weight launched is summed for the various systems. The SNAP-8 with electric propulsion results in the lowest weight at one year with increased savings thereafter. At five years, the total weight launched is 32,000 pounds less than photo-voltaic system in the Lockheed study. Without electric propulsion, SNAP-8 results in equal weight to the results of the photo-voltaic system in the Lockheed study at 4 years and lower weight at 5 years.

TABLE 5.8-1. YEARLY RE-SUPPLY REQUIREMENTS FOR SOLAR
PHOTO-VOLTAIC AND NUCLEAR SYSTEMS (40 KWe)

| | Solar Photo-Voltaic | | Man-Rated SNAP-8 | |
	Power System Study (LR-17228) (Lockheed)	Power System Study (GE)	Without Electric Propulsion	With Electric Propulsion
Power System, lbs	6,790	6,930	13,000	14,700
Fuel (One Year) lbs	15,275	16,635	7,985	2,250
Support Structure and Tankage for Fuel, lbs	2,110	2,300	1,100	230
Total	24,175 lbs	25,865 lbs	22,085 lbs	17,180 lbs

It is not exactly accurate to sum initial and re-supply weights as shown in Figure 5.8-1 because of the difference is cost per pound to deliver material to orbit. Weight at the initial launch is charged at $250/lb for the Saturn V; however, weight at replacement launches is charged at $1,000/lb for the SIB.

The comparison is more accurately presented in Figure 5.8-2 where cumulative launch cost for the various systems is summed. Initial launch costs vary over a range of only $2,000,000. Again SNAP-8 with electric propulsion results in minimum cost at 1 year and a cost advantage of $32,000,000 at 5 years. Without electric propulsion, SNAP-8 results in equal cost at 1 year and a cost advantage of $7,000,000 at 5 years.

5.9 SYSTEM COSTS

The development costs required to produce a 40 KWe solar cell system including deployable arrays of 10,000 ft^2 or to modify and adapt SNAP-8 as a man-rated system require a thorough evaluation to be definitive; however, the comparison is not complete without at least a gross assessment of these costs. Consequently, an assessment is made herein of the costs necessary to produce the first flight qualified solar cell and SNAP-8 power systems.
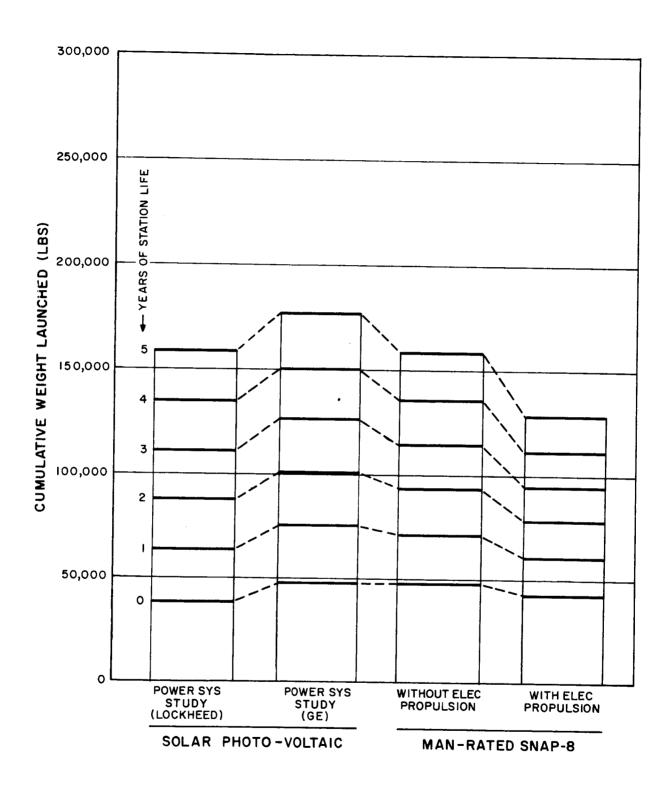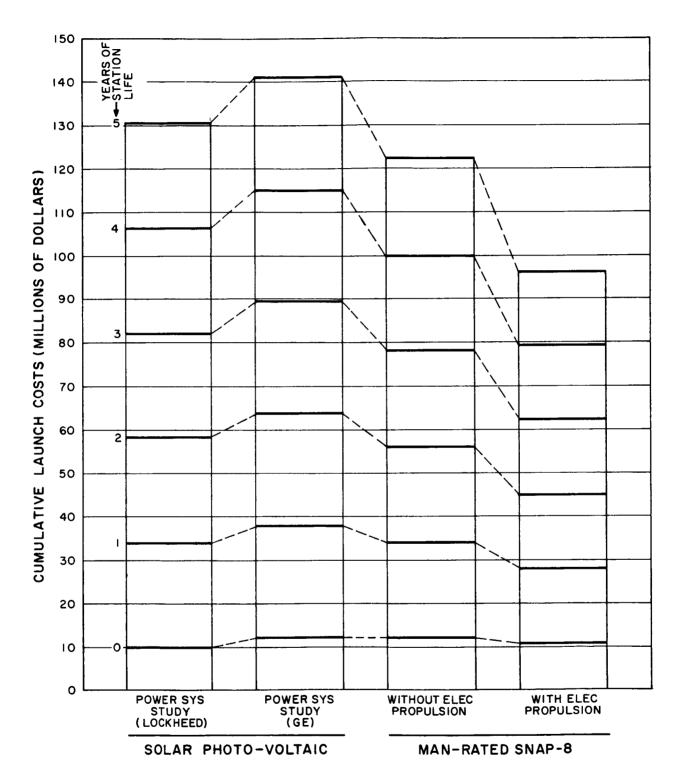
Figure 5.8-1 Effect of Initial and Re-Supply Weight

Figure 5.8-2 Cumulative Launch Costs based on 250 $/pound for Saturn V and 1000 $/pound for Saturn IB

Estimates of launch costs vary widely and the value of $1000/lb for the SIB is minimal. A more accurate estimate may be $4000/lb, in which case, the cost saving of SNAP-8 with electric propulsion would be increased from $32,000,000 to about $120,000,000 for a 5-year mission.

5.9.1 HARDWARE COST

It is possible to make reasonably accurate estimates of the costs for the manufacture, assembly, and testing of the systems upon completion of development.

Solar cell arrays in the size range of 0.1 to 1.0 KWe are presently being delivered at a cost of 700 to 1000 dollars per watt of unconditioned power from the solar panel. The 40 KWe solar photo voltaic system delivers 88.3 KWe from the arrays and extrapolated at the above rates, the cost per system would be 61,700,000 to 88,300,000. The cost of batteries, control systems, etc., are not included; however, they are negligible compared to the solar cell array cost.

Improvement in solar cell technology must be expected and this improvement will result in improved costs. The Lockheed study estimates the system cost at about 26,000,000 and an improvement, therefore, by a factor of 2.4 to 3.4. The GE study estimates the cost at vetween 28,000,000 and 45,000,000, and therefore a lower improvement factor.

The cost of a SNAP-8 system can be estimated on the basis of two pieces of information. First, the compact, packaged nuclear powerplants developed for the Army and Air Force range in price from $3,000,000 to $5,000,000 at a power level of 1 to 4 MW. Manufacturing, quality control, assembly, and testing standards are comparable to those for the space industry. The nuclear systems are larger and more complex than that of SNAP-8.

Second, eleven complete power conversion systems and their test stands, numerous additional components, and total system development for the SNAP-8 power conversion system is presently contracted at $63,000,000. Reactor development cost is an additional

Considering these factors, it is reasonable to expect that a SNAP-8 system can be manufactured, assembled, tested, and delivered to the launch site for $3,000,000 to $5,000,000. For four or five plants for an approximately five-year plant life and a 14-month life for each plant, the cost would be $12,000,000 to $25,000,000.

5.9.2 DEVELOPMENT AND FLIGHT QUALIFICATION COST

The development and flight qualification costs for the solar photo-voltaic system will likely include a ground test and a flight test. Since the arrays and power conditioning equipment are divided into 6 identical modules, it should be possible to test only 1/6 of the system. The range of estimates for the solar photo-voltaic system indicates that $40,000,000 per 40 KWe system will be attainable after development. One sixth of the above cost will be $6,660,000; however, in the smaller size and with first time development, costs will be somewhat higher resulting in a cost of about $10,000,000.

With a minimum of one ground test and one flight test, three fractional systems will be required because one spare will be necessary for the flight test. If the SIB booster at a cost of $25,000,000 each is used for the flight test, an additional $50,000,000 is added to the program costs. Then with $40,000,000 for the first full size flight system and an equal amount for a spare, the total cost is estimated at $160,000,000 as shown in Table 5.9.1.

TABLE 5.9-1 ESTIMATED TOTAL COSTS TO FIRST FLIGHT SYSTEM

Solar Photo-Voltaic	$ (10^6)$	Man-Rated SNAP-8	$ (10^6)$
Ground System Test of 1/6 Array	10	Man-Rating and Ground Tests	80
Flight Test of 1/6 Array		Flight Test of Full System	
Hardware (2)	20	Hardware (2)	20
Booster (2)	50	Booster (2)	50
Spare System	40	Spare System	5
First System	40	First System	5
	$160.0		$160.0

It is estimated that the cost to man-rate SNAP-8 and to run 2 or 3 additional ground tests would not exceed $80,000,000. This appears to be a conservative estimate since the components will have been proven by the tests on the reference system. The discussion (Section 5.9.1) indicates that cost per system will be in the range of

$3,000,000 to $5,000,000 after development and the higher value is assumed here. However, for the first flight test and spare, it is assumed that the cost will be increased 100% to $10,000,000 per system. Including the cost of two boosters and the cost of the first system plus spare, the total cost is estimated at $160,000,000.

5.9.3 SYSTEM COMPARISON

This comparison shows that:

- When all weights attributable to a power system are included, initial launch weight for solar photo-voltaic and SNAP-8 power systems are approximately equivalent.

- The yearly station resupply requirements for a SNAP-8 system can be about 7000 pounds lower than those of the solar photo-voltaic system, resulting in a saving of $32,000,000 to $120,000,000 over a station life of five years.

- The total cost required to provide the first flight qualified system of both types is about equal.

If, in fact, there is to be more than one station, then the nuclear system with its significantly lower cost per system will result in even greater program savings.

5.10 REFERENCES

1. Final Report "Study for an On-Board Electrical Power System for a Manned Orbital Space Station", LR 17228, by the Spacecraft Org. of Lockheed-California Co., Burbank, for NASA-Manned Spacecraft Center, Houston, Texas, Contract NAS 9-1307.

2. D. L. Kerr, "OSSS Power Supply Parametric Information," PIR 9741-097, Dec. 3, 1963

3. W. R. Cherry, "Solar Cells and the Applications Engineer", Astronautics and Aerospace Engineering, Vol. 1, No. 4, May 1963.

4. W. J. Schlotter, "Battery Design Parameters," PIR 9741-230, April 30, 1964.

5. W. J. Schlotter, private communication

6. "Study of a Rotating Space Station", NAS-9-1665, Feb. 4, 1964, LR-17516, Lockheed Aircraft Corporation.

6. SNAP-8 DEVELOPMENT PROGRAM RECOMMENDATIONS

Phases II and III of this study program have concentrated on adapting the present SNAP-8 Mercury-Rankine system to provide a man-rated system. Emphasis was placed on using the SNAP-8 components without modification, or at least with a minimum of modification. This approach will not produce a powerplant that is necessarily optimum for a particular application; however, it will generally produce a powerplant in minimum time and, possibly, at minimum cost.

There are design modifications that are desirable, provided that time is available and provided that the ultimate gains justify the costs of modifications. This section describes some modifications that warrant consideration within these provisos. The recommendations are divided into technical recommendations that principally affect the design of the SNAP-8 system and the modifications deemed advisable for man-rating and recommendations on the direction of further development for the man-rated SNAP-8 system.

6.1 TECHNICAL RECOMMENDATIONS

6.1.1 SHIELD WEIGHT AND MATERIAL OPTIMIZATION

This study parametrically considers the weights of shields composed of lithium hydride and tungsten. Continued investigations in the areas listed below will minimize the lapsed time and investment required to develop man-rated shields when required.

1. Lithium hydride and tungsten provide near minimum weights; however, there appears to be weight savings that can be obtained with alternate materials or with three component shields. In particular, substitution of either zirconium hydride or yttrium hydride for the lithium hydride in the volume adjacent to the reactor may reduce total shield weight. Additionally the high temperature properties of the two alternate hydrides are superior to those of lithium hydride.

2. The relative spacing and thicknesses of the layers of neutron and gamma shielding require optimization to provide maximum shielding for minimum weight.

3. Calculational techniques for predicting the secondary gamma scattering within the shield require improvement. This is particularly important because a large fraction of shield weight is provided to limit the station dose due to the shield gamma scattering.

4. There is a possibility of using station consumables as a substitute in part for permanently affixed shielding. In such a shielding arrangement, the outermost shield volume that receives a relatively lower dose could be divided into

separate compartments. These compartments can be filled with a consumable liquid at launch (e.g., liquid ammonia for arc-jet propulsion) that will be displaced by station liquid wastes (e.g., human waste) during operation. The fluids would be separated in each compartment by a bladder or bellows.

6.1.2 REACTOR SHIELDING ENVELOPE

Section 4.1.1, Third Topical Report, indicates that the reactor envelope can be significantly reduced by a modification of the reflector control elements. In a manned application where a 4π shield will likely be required, the reduction in reactor envelope results in a proportional reduction in shield size. The actual reduction in shield weight depends upon the particular configuration but it can be 15 to 30% for a change in envelope diameter from 26 inches to 20 inches. The saving on a 20,000 pound shield is therefore 3000 to 6000 pounds which is sufficient to justify a modification.

6.1.3 FAILURE OF MERCURY CONDENSER TUBES

A failure mode analysis shows that the present arrangement of components in the NaK heat rejection loop (HRL) is such that in the event of a condenser tube failure, NaK will leak from the HRL into the mercury loop. This will result in a fouling of the loop, a depletion of NaK from the HRL and system shutdown. The loop arrangement and system pressures that cause this condition are shown in Figure 6.1-1. The pressure difference across the condenser from the NaK to the mercury side varies from 20 to 30 psi as shown.

A more reliable system can be obtained if the system is re-arranged and the pressures reduced as shown in Figure 6.1-2. The loop is modified by two changes:

1. The pump is relocated from the condenser inlet to the condenser outlet thus making the condenser the low pressure point of the HRL.

2. The pressure throughout the HRL is reduced 12 psi resulting in a pump suction pressure of 3 psia.

These combined changes result in the loop pressures shown in Figure 6.1-2. The NaK side of the condenser is at a lower pressure at all points than the mercury side. Consequently, in the event of a tube failure, leakage will be from the mercury loop into the NaK loop. However, since the HRL is filled except for the expansion reservoir, the inleakage of mercury will be limited by the equalization of pressures between the loops.

MERCURY INLET ───────

16.4 PSIA
680 °F

36 PSIA
665 °F

MERCURY
CONDENSER
AND
SUB-
COOLER

NaK
HEAT
REJECTION
LOOP

33 PSIA
665 °F

Q   RADIATOR

11.5 PSIA
505°F

42 PSIA
496 °F

17 PSIA
495 °F

43 PSIA
496 °F

15 PSIA
495 °F

PUMP
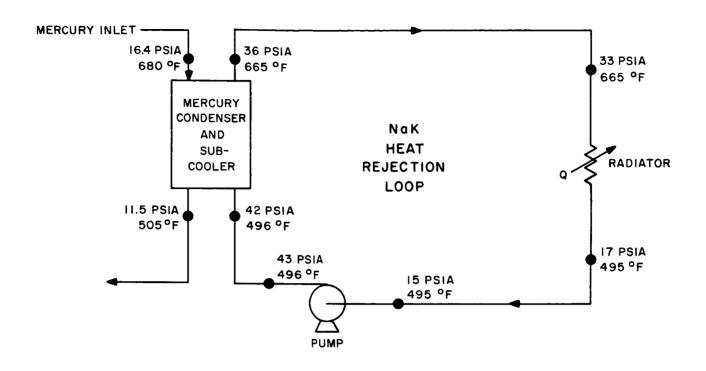
Figure 6.1-1.   Reference SNAP-8 Heat Rejection Loop

31 PSIA
665 °F

3 PSIA
664 °F

MERCURY INLET ───────

16.4 PSIA
680 °F

4 PSIA
664 °F

MERCURY
CONDENSER
AND
SUB-
COOLER

NaK
HEAT
REJECTION
LOOP

29 PSIA
665 °F

Q
RADIATOR

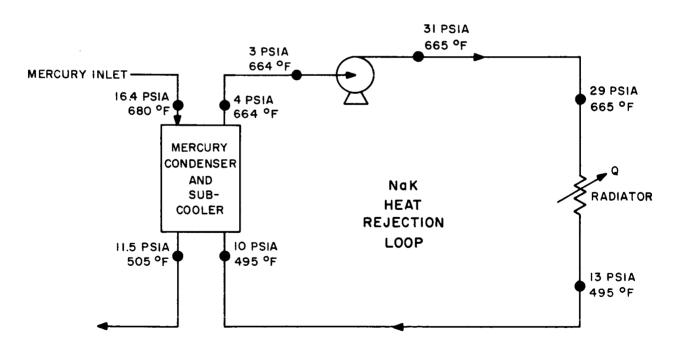11.5 PSIA
505 °F

10 PSIA
495 °F

13 PSIA
495 °F

Figure 6.1-2.   Modified SNAP-8 Heat Rejection Loop

HRL performance may be decreased somewhat due to the lowered volumetric heat capacity of the fluid; however operation could be continued. Some make-up of mercury to the mercury loop may also be required.

This change can be made without affecting the operation of any of the components. The pump will operate at lower suction pressure and higher temperature; however, the vapor pressure of NaK at 664°F is less than 1 mm Hg and, consequently, pump cavitation will not be approached. The increased temperature will be of no significance since the pump is practically identical to the primary NaK PMA that is designed to operate at 1100°F.

The one effect requiring consideration is that some parts of the HRL will be at a pressure below atmospheric. This is of no significance in a space environment, but it can cause difficulties in the ground test systems. Leaks in the low pressure regions will result in an inleakage of air into the loop that will be difficult to detect and correct. The air in the loop can also cause operational problems.

The ground test difficulties can be overcome and since it is more important to have a highly reliable system for operation in space than to have a simple system for ground test, it is recommended that this modification be incorporated in the HRL.
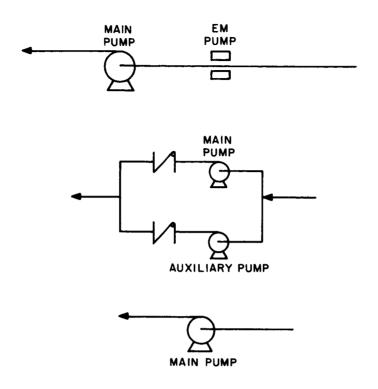
6.1.4 HEAT REJECTION LOOPS

It has been determined that flow must be continued in the radiator loops after system shutdown to prevent freeze-up of the loops. A flow rate 1/20 to 1/5 rated will be necessary. The flow can be provided as illustrated on the next page by, (a) an auxiliary EM pump, (b) a small pump in parallel with the main pump, or (c) by the main pump itself.

The EM pump has the advantages of high reliability and it can be included in the loop without additional valves. However, its efficiency is low and its weight is high.

A small pump with self lubricating bearings can be provided with a higher efficiency than the EM pump. However, it must be placed in parallel with the main pump and two check valves are required.

The main pump can be used to continue flow at a reduced rate by operation at below design speed as in the reference start-up sequence. Aero-jet General indicates that

6-4

MAIN
PUMP

EM
PUMP

MAIN
PUMP

AUXILIARY PUMP

MAIN PUMP

the pumps can operate without external lubrication or cooling at flows up to 30% of rated, which would be adequate. In this latter case, however, it must be recognized that the cause of powerplant shutdown may be either real or spurious indication of failure of the single pump available in the loop. If the indication is spurious, the pump may be restarted before freeze-up occurs; but if the failure is real, the loop will likely freeze before the necessary repair or replacement operations can be performed. Even with loop freeze-up, however, it may be possible to restart the loop if the loops are properly arranged. With radiators that support two independent sets of tubes and with contiguous layout of loop feeds and headers, it should be possible to conduct heat from the operating loop to the frozen loop and thereby return the frozen loop to operation.

This operational method will require proof in a test system.

6.1.5 ALTERNATE FLUIDS IN HEAT REJECTION LOOPS

In the manned application of SNAP-8, the equipment arrangement will be modified and all of the rotating components with the exception of the primary NaK pump, will be in a significantly reduced radiation field. Also the operational modes will be different in that storage of complete systems in space may be required and shut down and restart capability must be provided.

The reduced radiation environment allows a consideration of a greater number of fluids in the heat rejection loops. The requirements for storage and restart can more easily be met if alternate fluids with lower pumping points can be provided. Also, fluids with a lower pumping power will allow a greater net electrical output from the system.

6.1.6 NaK TO MERCURY BOILER

With the present boiler design, it is not practical to increase boiler reliability by the inclusion of a second redundant boiler for the reasons discussed in Phase II Report, Section 4.2.1, page 4-9. Also, the boiler operating conditions are such that the boiler tube material (9 Cr-1Mo) is at the limit of present material technology. For these reasons, it is expected that the boiler is the weakest single component in the Reference SNAP-8 EGS.

Boiler reliability can be increased in some degree in the modified system by a reduction in the severity of its operating conditions (Phase II Report, Section 4.2.5, page 4-43); however, a back-up or alternate design will provide additional assurance of obtaining a boiler with the reliability necessary for use in a man-rated system. Double tube boilers with the arrangement shown below have been used extensively in the nuclear industry and are one possibility. With such an arrangement, operation can be continued with a leaking tube and a leaking tube can be detected. The pressure of the non-circulating NaK between the tubes can be intermediate between the mercury and primary NaK loops: an increase in pressure will indicate a mercury-side tube leak and a decrease in pressure will indicate a NaK-side tube leak. With a means thus provided for detecting leaks before an injection of mercury into the NaK loop occurs, time is available for the valving in of a second or redundant boiler.
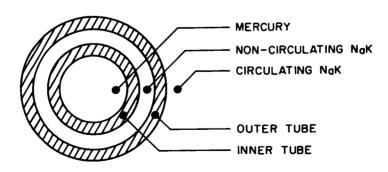

Figure 6.1-3. Double-Tube Boiler

The back-up boiler design will likely increase both boiler volume and weight over that of the present SNAP-8 boiler; however, both volume and weight are secondary considerations to lifetime and reliability in manned applications.

6.1.7 COOLANT-LUBE SYSTEM RADIATORS

The results obtained on up-rating SNAP-8 indicate that maximum power will be determined by the radiator area limitations of the booster. In the modified SNAP-8 system design, 700 ft^2 of the total available fixed radiator area of 2020 ft^2 is taken up by the two secondary coolant-lube radiators. Increased efficiency for the system components, of course, would raise the maximum system power through increased cycle efficiency and by increased primary radiator area.

A simple modification to the coolant-lube system will also reduce the secondary radiator area requirements. The components presently provide for separate coolant passages for seals, bearings, motors, and the alternator. High and low temperature coolant-lube systems can thus be provided. The high temperature system can move heat from the motors and bearings where higher temperature will not affect component reliability and the low temperature system can remove heat from the seals and instruments that must be maintained at the present temperature. The fraction by which radiator area can be reduced is shown in Figure 6.1-4 as functions of the temperature and the fraction of heat removed by the higher temperature coolant-lube system.

The modification obviously requires a separate coolant-lube loop with associated pumps and controls. The additional complexity will be warranted, however, if power greater than 60 KWe is required.

6.1.8 MAINTENANCE AND REPAIR TECHNIQUES

To provide for successful maintenance and repair, the following steps will be required:

1. The powerplant design must be reviewed in detail to define failure modes and their consequences.
2. A schedule of preventative maintenance, if any, must be prepared.
3. A determination must be made as to whether the various faults and failures will be corrected by repair, by component replacement, or by plant replacement.
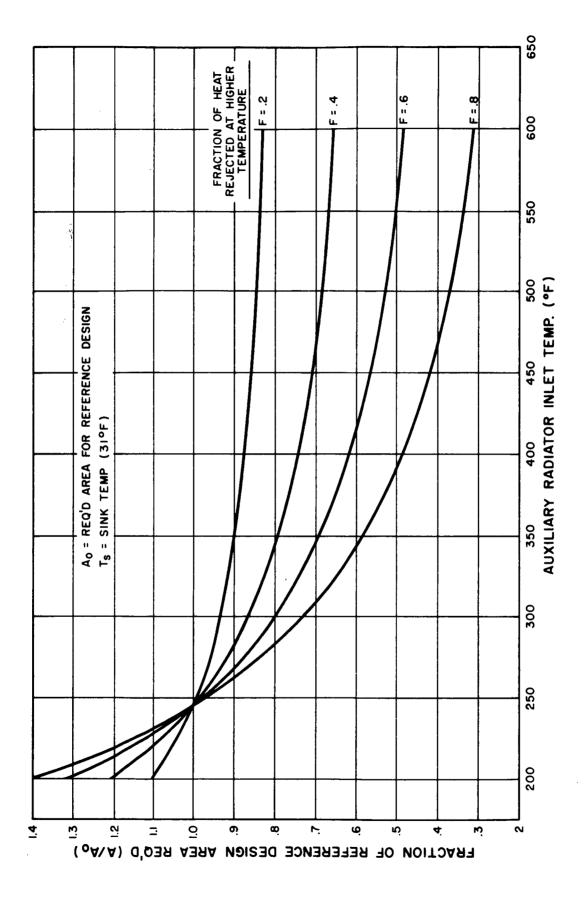4. Techniques must be developed for the repair and replacement operations judged desirable and necessary.

Figure 6.1-4. Secondary Collant-Lube Radiators

A ground test system is an essential part of proving these operations.

6.1.9 MERCURY LOOP

The modified SNAP-8 power system can incorporate two power conversion loops operating in parallel (Phase II, Section 6.1). This system, because of the load following control system, will undergo transients not expected in the reference SNAP-8. The transients will affect mercury loop flow rate, temperature, and pressure and will require changes in the loop mercury inventory. The result of the transients on the components has not been investigated; however, it is expected that the mercury pump will be principally affected. The varying pressure in the condenser and the changing flow rate may result in a decrease in pump suction and either partial or complete pump cavitation.

This condition can be prevented by the inclusion of additional liquid volume between the condenser and the pump and/or the inclusion of an inventory control system.

6.1.10 PARALLEL OPERATING POWER CONVERSION SYSTEMS

The cycle studies have shown that it is possible with the SNAP-8 components to operate parallel power conversion systems from one reactor at steady state. However, the studies did not include an examination of the transient control characteristics of such a system. Such an examination will be necessary before a final determination of feasibility can be made for the parallel loop system.

6.2 DEVELOPMENT RECOMMENDATIONS

6.2.1 DEVELOPMENT PROGRAM FOR MAN-RATED SNAP-8

A development program is required to define an orderly sequence of actions to produce a man-rated SNAP-8 system. The first need is for a program to provide ground test systems that can be used to demonstrate operation, prove maintenance and repair techniques, and for operator training. Systems on which an operator can gain the necessary competence in a matter of a few weeks or at most a few months will be essential to the program.

6.2.2 SNAP-8 SYSTEM AND COMPONENTS

The major components currently being developed in the SNAP-8 Program have been examined and determined to be applicable without modification in a man-rated SNAP-8

Power System for use with orbiting space stations. The components include sufficient design margin to allow an up-rating in system output to 45 to 50 KWe, also without modification.

Studies have also indicated that the man-rated power systems that incorporate these components will include significant design differences from the reference SNAP-8 system. Thus, although the man-rated and reference systems will use the same major components, the components will be applied in different system layouts.

The system differences will be sufficient to warrant the design, construction and operation of a man-rated system to serve as a test bed to examine shutdown and restart capability; modified instrumentation, control, and protection; the introduction of maintenance and repair capability; manned assistance in clearing system faults; component redundancy and the effect of more stringent radiation limitations. Such a system is considered essential to the successful adapation of the SNAP-8 components in a man-rated powerplant.

The test system would be extremely useful in training crews in operation, maintenance, and repair techniques as positively demonstrated in the Naval Reactors Program.

6.2.3 MAN-RATED SNAP-8 CONCEPTUAL DESIGN

This program has provided a conceptual design for the 3-spoke space station. It is reasonable to expect that the man-rated SNAP-8 system will undergo one or more demonstration flight tests prior to being used as the prime power source for a station. One definite possibility in considering flight tests is to use the SNAP-8 system as an experiment with one of the early stations. This has definite advantages in that power output can be used in the mission if operation is successful, development cost can be shared over more than one mission, and maintenance and repair techniques and their affect on reliability can be demonstrated in space.

Additional work is required to define the configuration that SNAP-8 would have as an experiment. There are advantages if the configuration, equipment arrangement, operation, etc., are identical to those of the intended application; however, there will likely be compromises required to accommodate the system within the limitations of the smaller station and the smaller booster.

6.2.4 MAN-RATED SNAP-8 DESIGNS FOR VARIOUS MISSIONS

The flight tests necessary to qualify a man-rated SNAP-8 system will be a major fraction of the total cost required to produce the first flight system. A definite conclusion cannot be made as to whether a flight test will be necessary for each major configuration change; however, it is obvious that a test does much to increase confidence in the system.

SNAP-8 is currently being considered as the power supply for Manned Space Stations and Manned Lunar Bases. If different powerplants must be qualified for each mission, then flight demonstration costs are doubled. Consideration should be given to developing a single powerplant that is adequate but not necessarily optimum for both missions. Development costs could be shared. The comparison of the increased costs to each mission resulting from using a single powerplant design versus the decreased development and flight demonstration costs would determine whether a single or independent system designs should be developed.

6.2.5 POWERPLANT WEIGHT AND LIFETIME

Low powerplant weight for long duration missions (greater than one year) is only one indicator of desirability. This study has shown that the total logistics requirements ascribable to a power system over the mission duration must also be considered in addition to initial weight to define a minimum weight and cost system.

For nuclear systems, the cost to manufacture and assemble a system is negligible compared to the cost to integrate and launch a system into orbit. Consequently, the total launch costs incurred in fulfilling a given mission can be used as an index to compare systems. For a given mission, the total cost will be the sum for the initial and support launches.

$$
\begin{aligned}
\text{Total Launch Cost} &= (\text{Initial Launch}) \ (\text{Initial Launch}) \ + \\
\text{for Mission} \quad & \text{Weight, lb} \qquad \text{Cost, \$/lb} \\[6pt]
& (\text{Replacement Launch}) \ (\text{Replacement}) \ (\text{No. of Replacement}) \\
& \quad \text{Weight, lb} \qquad \quad \text{Launch Cost} \quad \text{Launches} \\
& \qquad\qquad\qquad\qquad\quad \text{\$/lb}
\end{aligned}
$$

A significant conclusion can be drawn from this simple expression. The replacement launch cost (dollars/pound) is about 4 times greater than the initial launch cost.

Consequently, depending upon whether the number of replacement launches is 1, 2, 3, or 4, up to 4, 8, 12, or 16 pounds may be "spent" in increased weight on the initial plant to reduce the replacement launch weight by one pound. This indicates strongly that first plant weight should be sacrificed to reduce logistics requirements and to increase plant lifetime.

6.2.6 STABILITY OF ROTATING SPACE STATIONS

Station control is simplified if the ratio of the moment of inertias* is maximum for rotation about the spin axis (See discussion in Phase II Report, Section 5.1). Powerplants may be located generally on the spin axis or in the spin plane and with the present philosophy for station stability control, must result in a maximum moment ratio about the spin axis in both locations. The powerplant weights for spin axis and spin plane mounting can be significantly different due to the difference in shielding requirements at the alternate locations. This can present a serious integration compromise in that the mounting position favored for integration, logistics, and operational reasons may result in greater shield weights.

Considerable additional flexibility can be attained in integration choices if station control with the ratio of movement of inertias minimum about the spin axis can also be considered. This is illustrated by the three-spoke station discussed in II, Section 5.1. Consequently, investigation of the possibility of controlling rotating stations with moment ratios less than 1.0 is warranted. The trade-off between added fuel consumption and control system complexity versus reduced shield weight is particularly important.

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*Ratio of moment inertia about spin axis to moment of inertia about axis in spin plane.

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